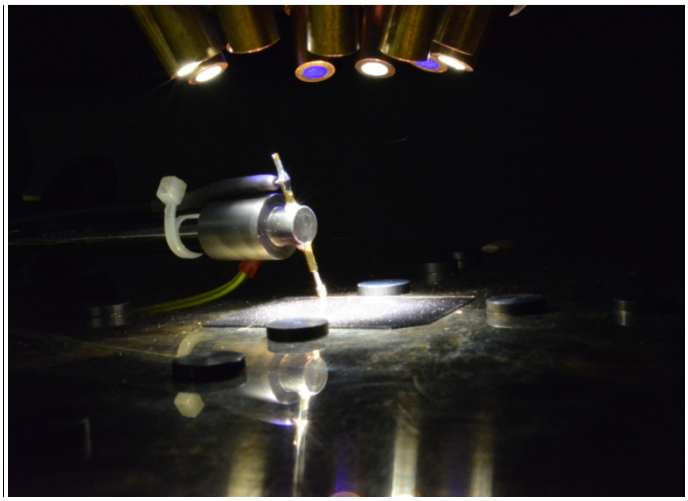
BENTHAM

PVE300- 4J FILTER SET

CHARACTERISATION OF FOUR-JUNCTION SOLAR CELLS



USER MANUAL

Version 1 - March 2014

Bentham Instruments Limited

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TABLE OF CONTENTS

1 INTRODUCTION

Thank you for your purchase of the Bentham PVE300 4J Filter set. The documentation for this product consists of this User's Manual with reference made to specific component manuals where further information is sought. To get the most from this measurement system, please be sure to read all instructions thoroughly and keep them where they will be read by all who use the product.

2 GUARANTEE

Bentham Instruments warrants each instrument to be free of defects in material and workmanship for a period of one year after shipment to the original purchaser. Liability under this warranty is limited to repairing or adjusting any instrument returned to the factory for that purpose. The warranty of this instrument is void if the instrument has been modified other than in accordance with written instructions from Bentham, or if defect or failure is judged by Bentham to be caused by abnormal conditions of operation, storage or transportation.

This warranty is subject to verification by Bentham, that a defect or failure exists, and to compliance by the original purchaser with the following instructions.

Before returning the instrument, notify Bentham with full details of the problem, including model number and serial number of the instrument involved. After receiving the above information, Bentham will issue an RMA reference number and provide shipping instructions.

After receipt of Shipping instructions, ship the instrument "carriage paid" to Bentham. Full liability for damage during shipment is borne by the purchaser. It is recommended that instruments shipped to us be fully insured and packed surrounded by at least two inches of shock-absorbing material. Specific transit packaging as used in Monochromators etc. must be installed.

Bentham reserves the right to make changes in design at any time without incurring any obligation to install same on units previously purchased.

This warranty is expressly in lieu of all other obligations or liabilities on the part of Bentham, and Bentham neither assumes, nor authorises any other person to assume for it, any liability in connection with the sales of Bentham's products.

NOTHING IN THIS GUARANTEE AFFECTS YOUR STATUTORY RIGHTS.

3 NOTICE FOR CLIENTS IN EUROPEAN UNION

This product is designated for separate collection at an appropriate collection point. Do not dispose of as household waste.

Bentham are fully WEEE compliant, our registration numberis WEE/CB0003ZR.

Should you need to dispose of our equipment please telephone +44 (0) 113 385 4352/4356, quoting account number 135419

4 CONTACT BENTHAM

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5 SYSTEM REQUIREMENTS

Bentham PVE300 with two bias sources and 474 transformer having banana plug primary coil inputs

Keithley 2400-LV Source Measurement Unit (or equivalent)

Four cables terminated in a BNC connector to one end, banana connector to other and one cable terminated in a BNC connector to one end, spade connector to other

Figure 1: PVE300 with two bias sources

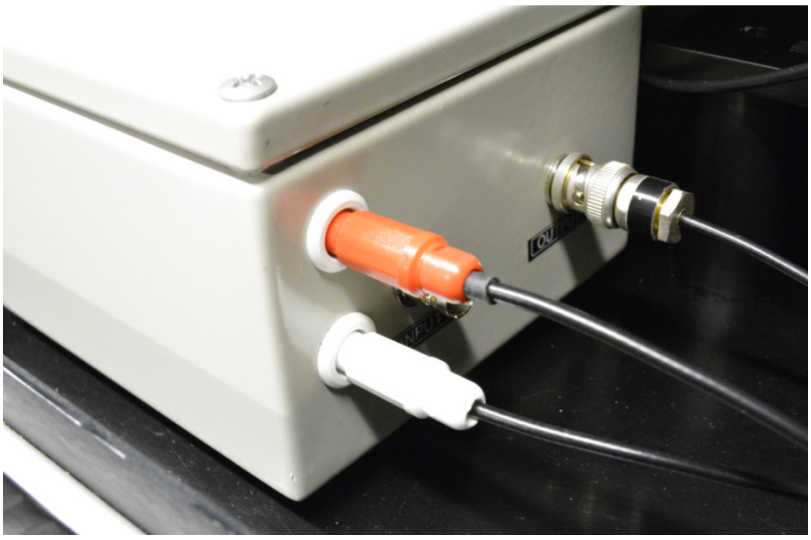


Figure 2: 474 Transformer with banana plug primary coil inputs

6 FILTER SET CONTENTS

Part Number	Filter Type	Filter Description	Use with Junction(s)..	Label
13597	Hot mirror	Reflects IR > 750nm	2, 3, 4	J 2/3/4-Bias A ↓
13597	Hot mirror	Reflects IR > 750nm	2,3	J 2/3-Bias B ↓
13598	KG1	Absorbs IR > 800nm	3, 4	J 3/4-Bias A ↑
13600	BG23	465nm band pass	2	Jcn 2-Bias A ↑
13610	BG3	465nm short pass	4	Jcn 4- Bias B ↑
13611	B410	538nm short pass	4	Jcn 4- Bias B ↓
13612	RG715	715nm long pass	1	Jcn 1- Bias A ↑

Table 1: Four junction filter set

Four labels are supplied for attachment to the two PVE300 bias sources to aid in the correct installation of filters for the avoidance of heat-related damage. Please observe recommendations.

For further information on the filter labelling system suggested, please read section 7.

7 FILTER LABELLING SYSTEM

The PVE300 bias source consists of a 50W quartz halogen lamp and uses an elliptical reflector to couple a maximum light to the fibre bundle that transports light to the sample plane. Between the lamp and the fibre bundle are provide two locations in which to install filters to control the spectrum of the bias source.

The coupling of the high irradiance at the filter plane and the absorption characteristics of certain filters will result in catastrophic damage. The following guidance ensures that those filters susceptible to damage are the second to be installed (where applicable) and that they be installed in the filter location furthest from the source.

Four labels, marked with direction indication arrows, have been shipped for attachment to each bias source, to complement the labelling on each filter. The naming of source A and B are arbitrary and may be defined by the user. The labels should be affixed as shown in figure 3.

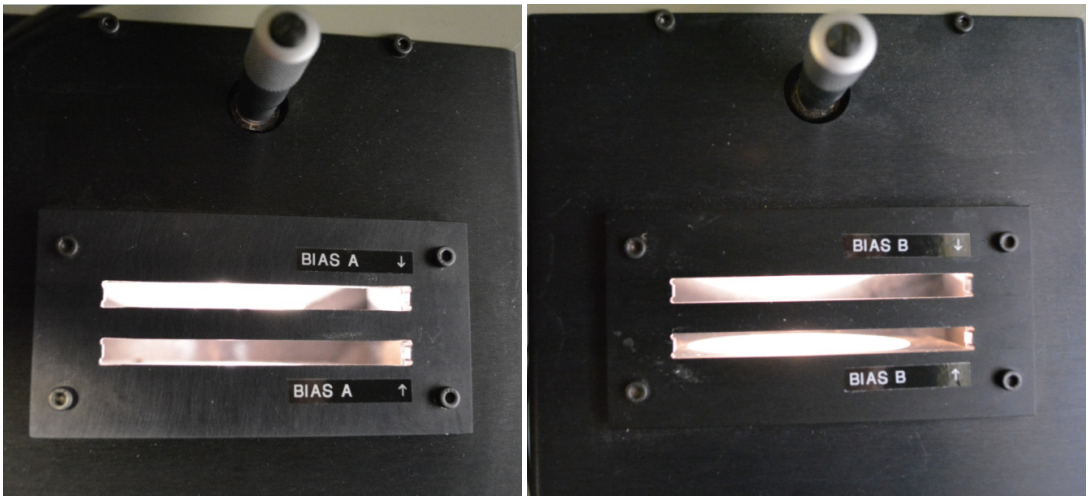


Figure 3: Bias source labelling convention recommended

In installing filters, there are two rules two observe:-

1. Always insert the filter that should be installed nearest the source (filter labelled ↓) first
2. When installing filters, ensure the arrow on the filter matches that one the source, thereby ensuring the filter is in the correct location.

As an example, for the second junction, first install filter 13597 then filter 13600. To do the reverse might result in the damaging of filter 13600.

Figure 4: For the second junction, install filter 13597 first, then install filter 13600 in bias A.

8 OVERVIEW OF MEASUREMENT PROCEDURE

8.1 INTRODUCTION

It is not possible to measure the spectral responsivity/ EQE of component sub-cells of a monolithic four junction solar cell separately since they are epitaxially grown on one substrate and interconnected by tunnel diodes. The spectral response of a sub-cell is therefore measured by putting it into current limitation by applying an appropriate light bias which leads to an excess photocurrent in all other sub-cells in the device. In this manner, the photocurrent generated by the four junction device is defined by the response to the monochromatic probe of the sub-cell under consideration.

As a first approximation, one should employ a light bias having significantly greater emission in the spectral range of response of all non-tested sub-cells (or indeed with no emission in the range of the sub-cell under test) to ensure they are operating at excess photocurrent.

With appropriate light biasing in place one can, in the case of junctions one, two and three, directly measure the spectral response / EQE of the sub-cell under test over a suitable wavelength range.

A step-by-step measurement procedure is provided in section 9.

For further information, please refer to the PVE300 manual.

8.2 THE SPECIAL CASE OF FOURTH JUNCTION

Since the current of the four junction cell is limited by that of the sub-cell under test, it follows that the non-tested cells with excess photocurrent operate close to their V_{oc}. In maintaining the four junction device under short circuit conditions, a negative voltage approximately equal to the sum of the V_{oc} of the other cells is placed across the tested subcell.

In the case of the first, second and third sub-cells with good I-V characteristics, this has little or no impact. On the other hand, low band-gap materials, such as the Germanium fourth junction often exhibit non-ideal properties such as a low shunt resistance or a low reverse breakdown voltage, which may have an impact on the spectral response measurement, leading to erroneous results both within and without the spectral range in which the sub-cell responds.

Outside the spectral range of the subcell under test, the photocurrent generated by the monochromatic probe gives rise to an increase in operating voltage of the current-limited non-tested cells. Since the four junction cell is maintained under short circuit conditions, this gives rise to a corresponding reduction in the operating voltage of the subcell under test. Where the sub-cell under test exhibits shunted reverse characteristics, this drop in voltage leads to an increase in J_{sc}, showing a response where one is not expected.

Within the subcell response range, the presence of the monochromatic probe will directly lead to an increase in J_{sc}, shifting the current-limited non-tested cells to lower operating voltage. Since the four junction cell is maintained under short circuit conditions, this gives rise to an increase in the voltage of the sub-cell under test. Where the sub-cell under test exhibits shunted reverse characteristics, the measured photocurrent is lower than the increase of J_{sc} in response to the monochromatic probe, leading to the reporting of lower spectral response/ EQE.

Shifting the external voltage of the cell will tend to minimise both of the above effects: in moving to higher gradient regions of the I-V curve of the non-tested cells, lower shifts in subcell operating voltage are encountered, giving rise to less variation in the current of the cell under test.

Furthermore, optimising the light bias to increase the photocurrent generated by the non-tested sub-cells leads to increased gradient of the I-V curve in the proximity of their operating voltage, whilst reducing the photocurrent generated by the subcell under test will lead to a reduction of operating voltage closer to V_{oc} where the gradient of the I-V curve is steepest. Both will give rise to less variation in the current of the cell under test.

8.3 SAMPLE MOUNTING

Since the device under test will be exposed to two bias sources, it is important to ensure that the temperature-controlled vacuum mount temperature control is set, typically to 20°C, that the vacuum is on, and that all open vacuum points are closed with the provided “pennies” to ensure good thermal and electrical contact throughout measurement.

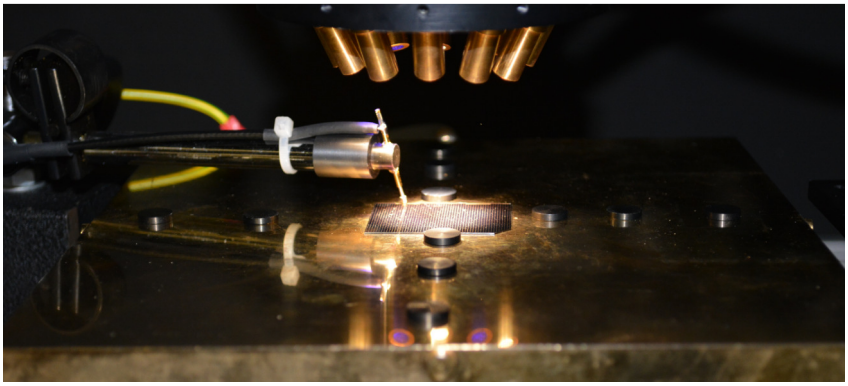


Figure 5: Sample mounted on temperature-controlled vacuum mount and all open vacuum points closed using “pennies”

8.4 PVE300 LIGHT BIASING

In the PVE300, light biasing of four junction cells is achieved by the use of two bias sources and this set of filters. In the case of the first junction, only one of the two bias sources is required.

The combination of filters required to test each junction – applying light bias to all non-tested junction- is described in table 2, in which the reference to “source” and “chamber” relates to the position of the filter, in accordance with the guidance provided in section 7.

Junction	Spectral Range	Bias A		Bias B	
		Source	Chamber	Source	Chamber
1	300-800	-	13612	-	-
2	300-1000	13597	13600	-	13613
3	800-1800	13597	13598	13597	-
4	1000-1800	13597	13598	13611	13610

Table 2: Four junction cell filter requirements

Each bias source is fitted with a solenoid-controlled shutter which may be opened/ closed through the Benwin+ utilities menu/ PV Bias Control. For the avoidance of confusion, it would make sense to designate the first source in the last as Bias A. Where the reverse obtains, one can simply exchange the three-pin SAM control line from the monochromator between the two sources.

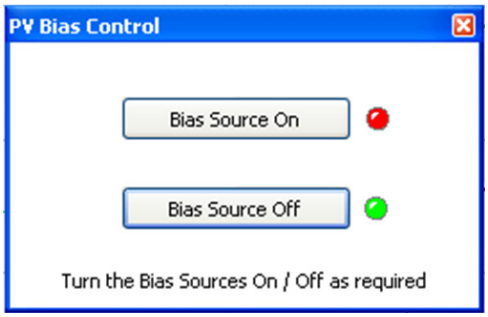


Figure 6: Benwin+ PV Bias Control GUI

Finally, it should be assured that the variable slit of both bias sources is fully open to 10mm.

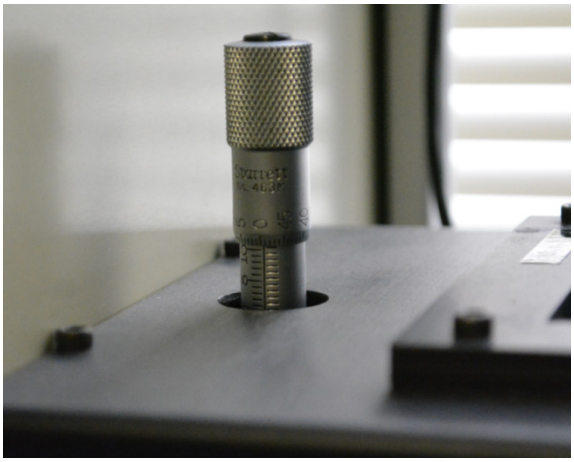


Figure 7: Bias source slits opened fully to 10mm

8.5 PVE300 VOLTAGE BIASING

Voltage biasing is achieved by connecting the Keithley 2400 Source Meter across the primary coil of the 474 transformer. The Keithley 2400 is controlled manually throughout.

Figure 8: Voltage biasing with the Keithley 2400 Source Meter

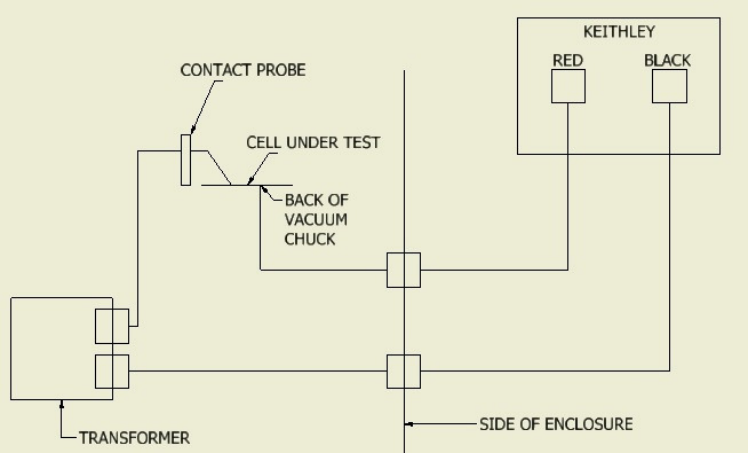


Figure 9: Voltage biasing electrical connection

A step-by-step fourth junction measurement procedure using the Keithley 2400 is provided in section 9.7

For further information, please refer to the Keithley 2400 user manual.

9 MEASUREMENT OF FOUR JUNCTION CELL

9.1 SYSTEM SET-UP

1 Power on PVE300 system and allow a warm up period of at least fifteen minutes

2 Select a probe size appropriate for the sample under test. Where the device electrodes are small one need not be concerned about under-filling the space between electrodes.

The larger the beam used, the more optical power is incident on the device under test, resulting in better the signal to noise ratio

3 Ensure 218 optical chopper controller powered on and displaying frequency of 300 on dial

4 Ensure 45° beam divert mirror to upper of PVE300 chamber is in left-hand position allowing beam to reach sample plane

5 Run Benwin+, and initialise in the transformer configuration

9.2 SYSTEM CALIBRATION

1 Install DH-Si reference silicon photodiode in PVE300.

2 Connect DH-Si to transformer input using short, thick BNC cable.

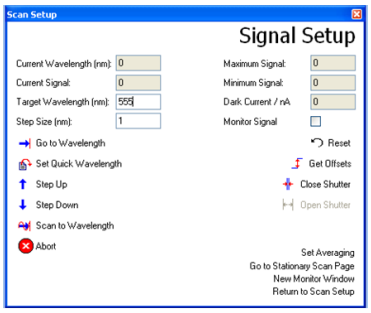
Ensure output of transformer connected, through PVE300 wall, to 474 amplifier input.

Ensure 474 amplifier output connected to lock-in amplifier input.

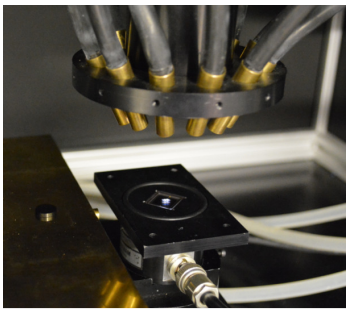
3 To align the DH-Si to the monochromatic probe beam, in Benwin+ go to scan/ signal setup.

Input target wavelength (0nm = white light or for example 555nm = green light).

Hit go to wavelength.



4 Adjust the position of the DH-Si to ensure the beam falls entirely within its active area

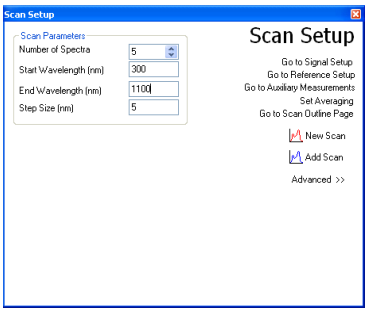


5 Go to scan/ scan setup.

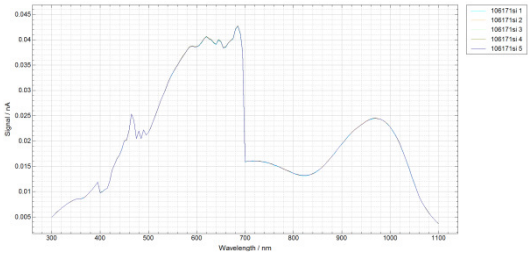
Input start wavelength 300nm, end wavelength 1100nm and step size 5nm.

It is recommended for calibration to perform more than one scan to ensure system stability, here five have been chosen.

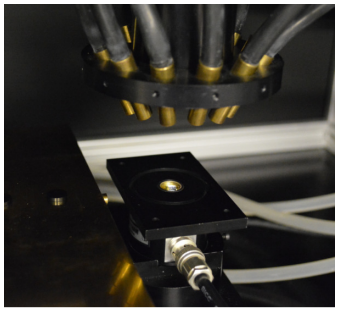
Hit new scan.



6 At the end of scan, save to file, giving appropriate name.



7 Install DH-Ge reference germanium photodiode.



8 Connect DH-Ge to transformer input using short, thick BNC cable.

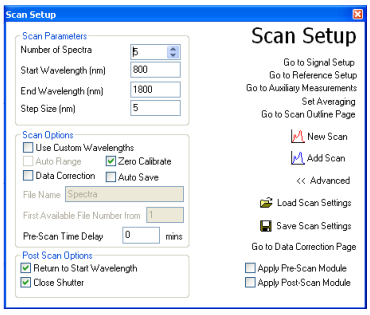
Use signal setup to ensure the beam falls entirely within the device active area.

9 Go to scan/ scan setup.

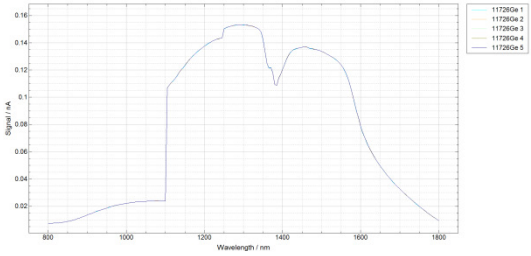
Input start wavelength 800nm, end wavelength 1800nm and step size 5nm.

It is recommended for calibration to perform more than one scan to ensure system stability, here five have been chosen.

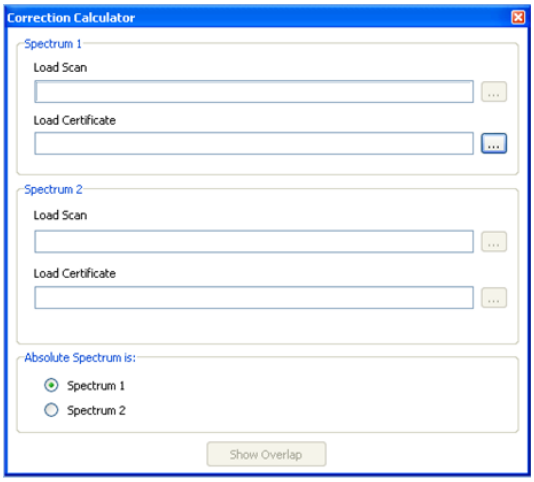
Hit new scan.



10 At the end of scan, save to file, giving appropriate name.



11 To combine both calibrations into one single calibration factor, go to utilities/ correction calculator.

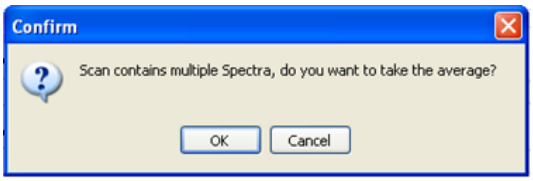


12 Spectrum 1:

Load Scan, hit "…" button, load just saved measurement of DH-Si.

When prompted, say OK to take average.

Load certificate, hit "…" button, load calibration file (*.bcf) of DH-Si.



13 Spectrum 2:

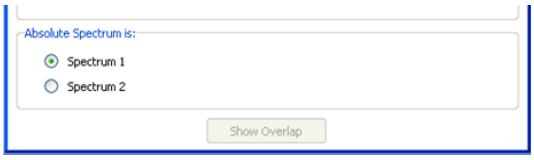
Load Scan, hit "…" button, load just saved measurement of DH-Ge.

When prompted say OK to take average.

Load certificate, hit "…" button, load calibration file (*.bcf) of DH-Ge.

14 Ensure spectrum one selected as absolute spectrum.

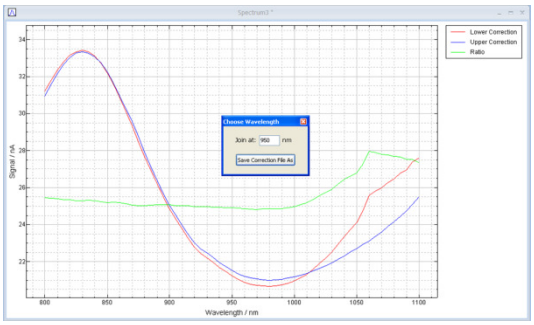
Hit Show overlap.



15 You will be presented with the calibration factors of both DH-Si and DH-Ge detectors in the overlap region, with the ratio of the two shown in green.

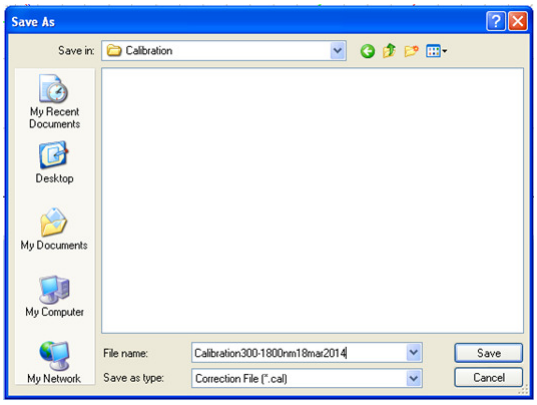
By default the wavelength at which the two are put together is 950nm.

Hit “Save correction file as”.



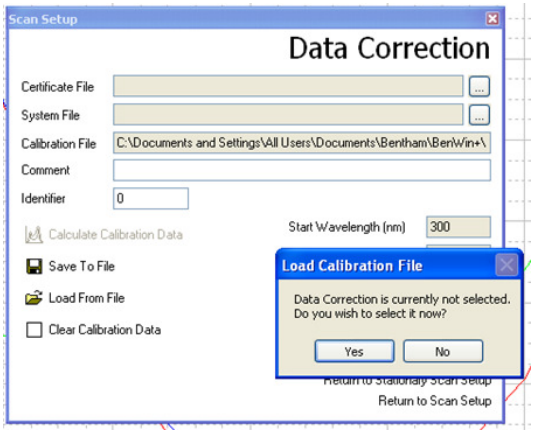
16 In save dialogue box input name for this calibration file (*.cal), hit save.

A message confirms the output of this utility. Hit OK and close the overlaps window (no need to save).



17 To apply this correction file, go to scan/ data correction, hit “Load from file”.

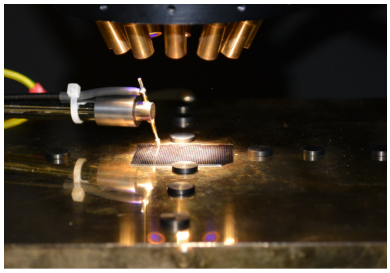
On prompt say “Yes” to apply data correction.



18 The system is now calibrated to measure spectral response 300-1800nm

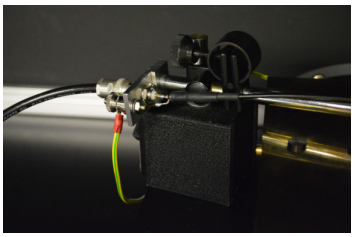
9.3 SET-UP SAMPLE UNDER TEST

1 Position sample on temperature-controlled vacuum mount.

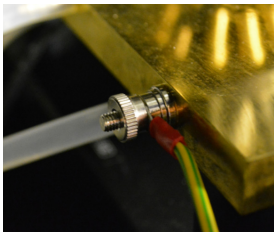


2 Power on VC-20-TE, switching on water flow, temperature control to 20°C and vacuum.

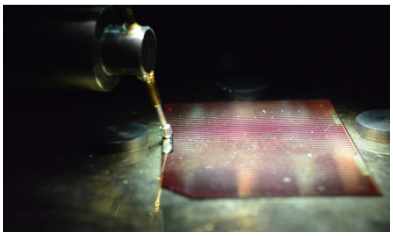
3 Connect probe to transformer input using short, thick BNC cable.



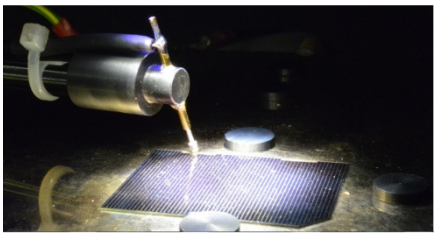
4 Ensure probe connected to temperature controlled mount using cable terminated in spade connectors to either end (green and yellow cable).



5 Move probe to make electrical connection with device under test.



6 Cover open vacuum points with “pennies”.

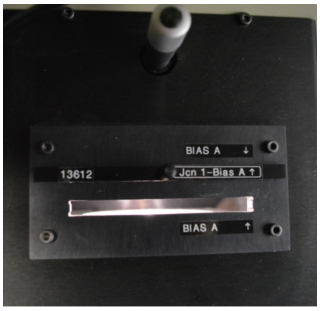


7 Use signal setup to align beam to sample.

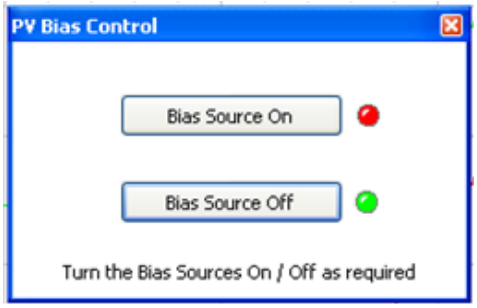
8 The four junction cell is now ready for measurement.

9.4 MEASUREMENT OF FIRST JUNCTION

1 Install filter 13612 into bias A position nearest to the PVE300 chamber.



2 Go to utilities/ PV bias control, switch on bias source A.



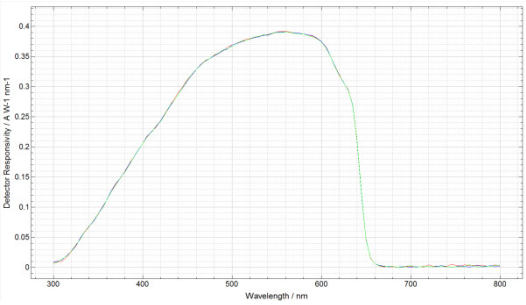
3 Go to scan/ scan setup.

Input start wavelength 300nm, end wavelength 800nm and step size 5nm.

The end user can choose how many scans required.

Hit new scan.

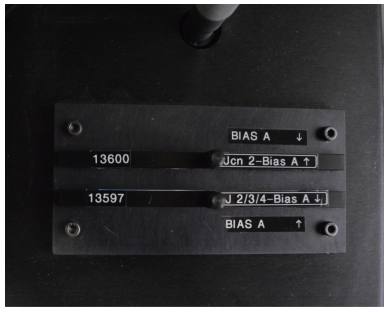
4 At the end of scan, save results.



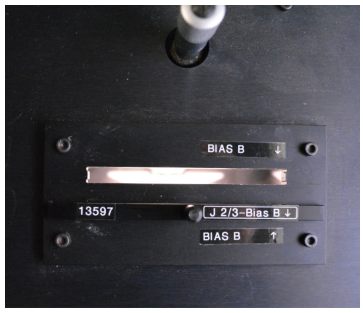
9.5 MEASUREMENT OF SECOND JUNCTION

1 Remove filter 13612 and install filter 13597 into bias A position nearest to the source.

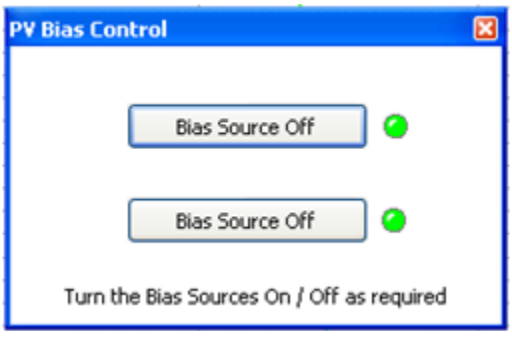
2 Install filter 13600 into bias A position nearest to the PVE300 chamber.



3 Install filter 13597 into bias B position nearest to the source.



4 Go to utilities/ PV bias control, switch on both bias source B (A already on).



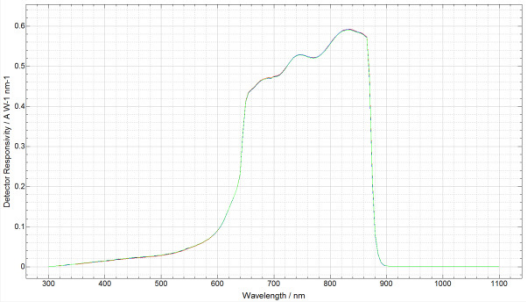
5 Go to scan/ scan setup.

Input start wavelength 300nm, end wavelength 1000nm and step size 5nm.

The end user can choose how many scans required.

Hit new scan.

6 At the end of scan, save results

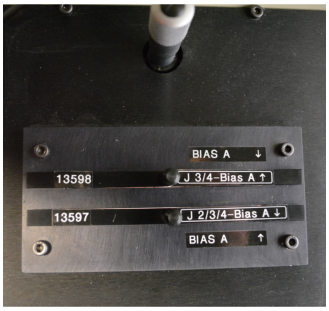


9.6 MEASUREMENT OF THIRD JUNCTION

1 Remove filter 13600 and install filter 13598 into bias A position nearest to PVE300 chamber.

Leave filter 13597 in bias B.

Since the last measurement, both bias sources are open.



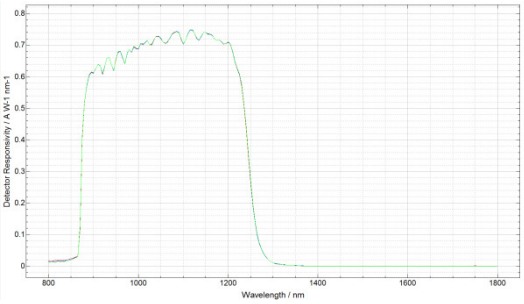
2 Go to scan/ scan setup.

Input start wavelength 800nm, end wavelength 1800nm and step size 5nm.

The end user can choose how many scans required.

Hit new scan.

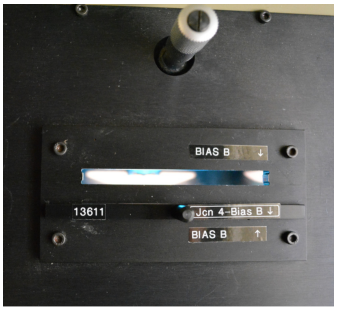
3 At the end of scan, save results.



9.7 MEASUREMENT OF FOURTH JUNCTION

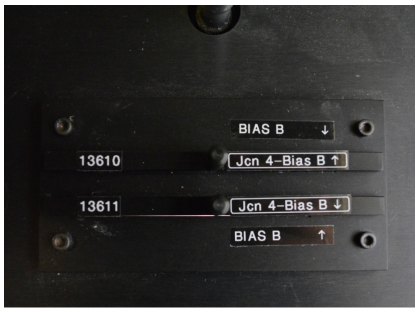
1 Leave filters 13597 and 13598 in bias A.

Remove filter 13597, and install filter 13611 in bias B position nearest to the source.



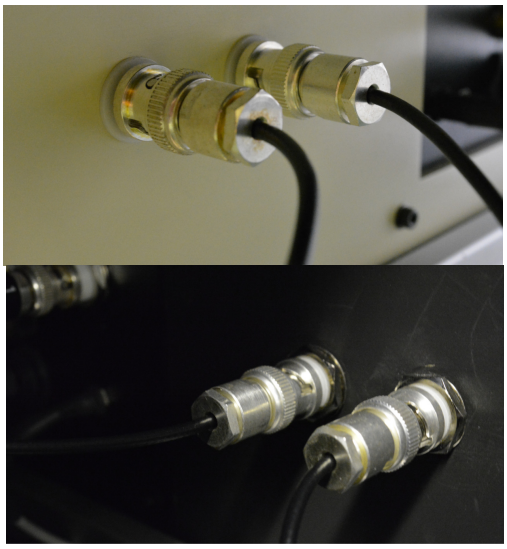
2 Install filter 13610 in bias B position nearest to the PVE300 chamber.

From the previous measurement, both bias sources remain open.



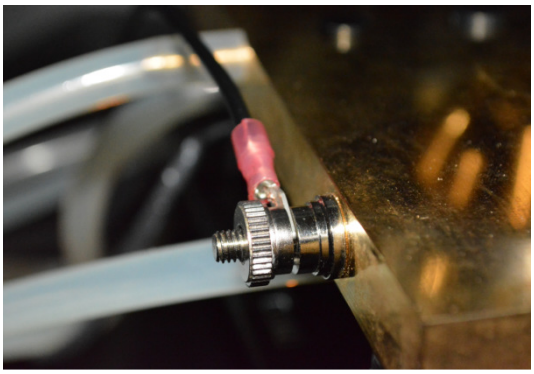
3 Power on Keithley 2400 and connect input/ output ports to PVE300 wall using banana plug to BNC cables.

4 PVE300 input from Keithley 2400.

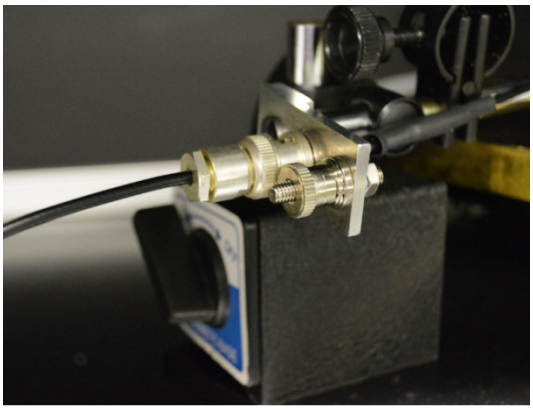


5 Remove the link between the probe and vacuum mount.

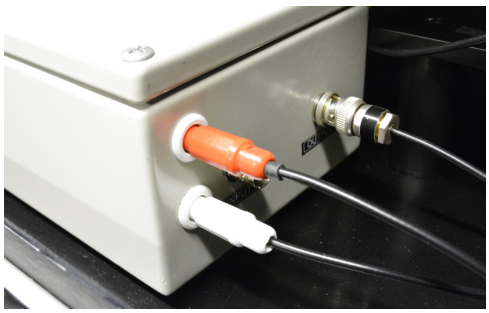
Connect the positive Keithley input/ output to the vacuum mount using a BNC to spade connectorised cable.



6 Connect the probe to one side of the transformer using a BNC to banana cable.



7 Connect the negative input/ output from the Keithley to the other side of the transformer using banana to BNC cable.

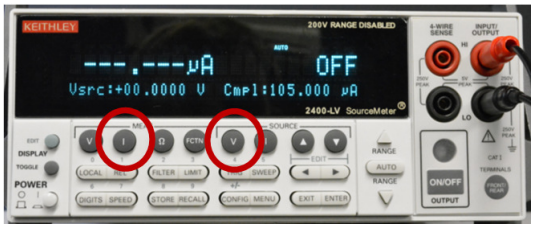


8 The transformer output should remain connected as before.

9 On Keithley front panel:-

Hit SOURCE V

Hit MEAS I



10 Hit EDIT twice to make Cmpl (Compliance) flash.

Hit △ several time to take compliance range from µA to A.

Using SOURCE ◀▶ arrows to change digit to be changed and increase/ decrease with ▲▼ arrows, change Cmpl value to 1.0000A.

11 Hit ON/OFF. The photocurrent generated by the bias sources will be shown.

12 If Cmpl flashes, ensure AUTO is selected

13 Hit edit once to change the source voltage.

Use ◀▶arrows to change digit to be changed and increase/ decrease with ▲▼ arrows.

It is recommend to change in 0.1V steps.

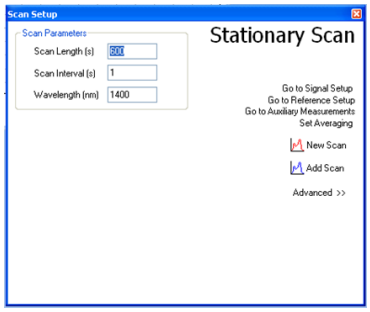
14 One seeks the voltage at which the output of the fourth junction is optimised.

In the first instance, increase the voltage across the cell to determine the voltage at which one crosses from a negative to a positive photocurrent.

15 One can refine this process by monitoring the signal output from the sub-cell under test as a function of voltage applied.

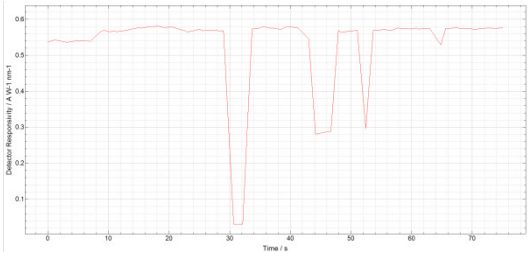
Go to scan/ stationary scan setup.

Define a scan of 600s scan length, interval 1s at a wavelength at which the fourth junction responds, such as 1400nm.



16 Starting 0.5V volt lower than the point at which it was found that the photocurrent changes sign, slowly increase the voltage in 0.1V steps and observe the changes in the measured signal.

Here the signal is increased then at 3.0V, the signal drops dramatically.



It is suggested that a resolution of 0.1V is sufficient in the determination of voltage to apply for the measurement of spectral response.

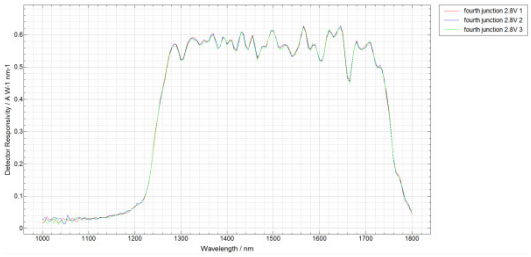
17 Go to scan/ scan setup.

Input start wavelength 800nm, end wavelength 1800nm and step size 5nm.

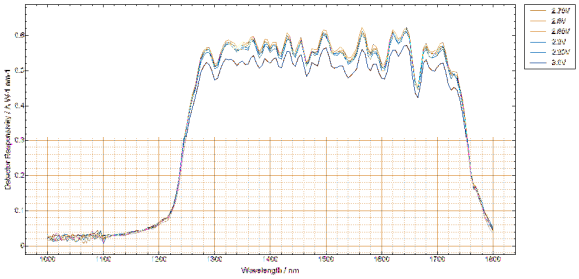
The end user can choose how many scans required.

Hit new scan.

18 At the end of scan, save results.

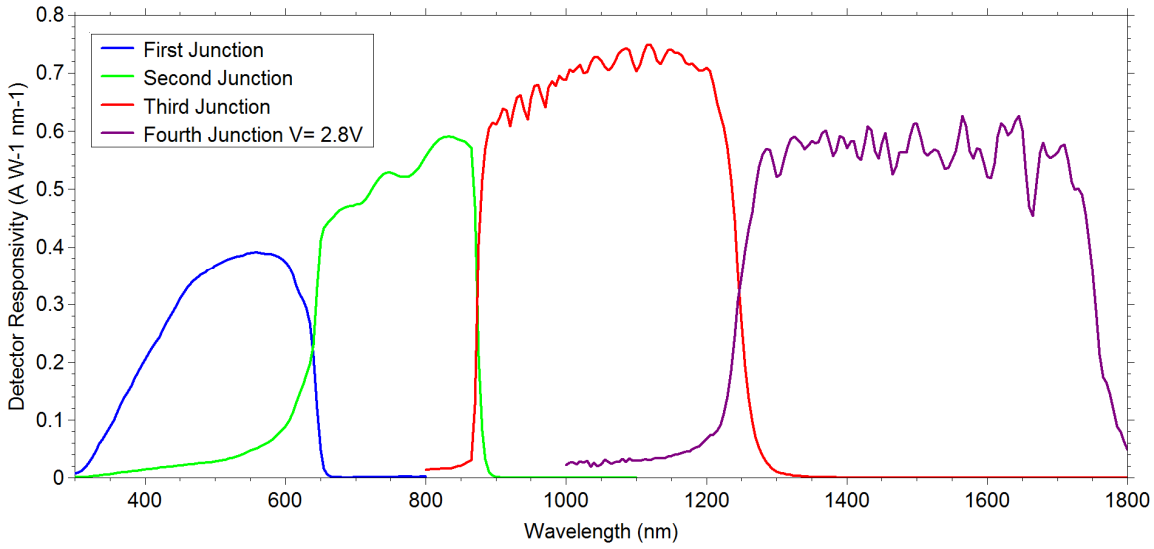


19 One can where desired repeat the measurement at different bias voltages to explore the variation of spectral response.



10 FINAL RESULTS

Example final results of the spectral response and EQE of a four junction solar cell follows.



v