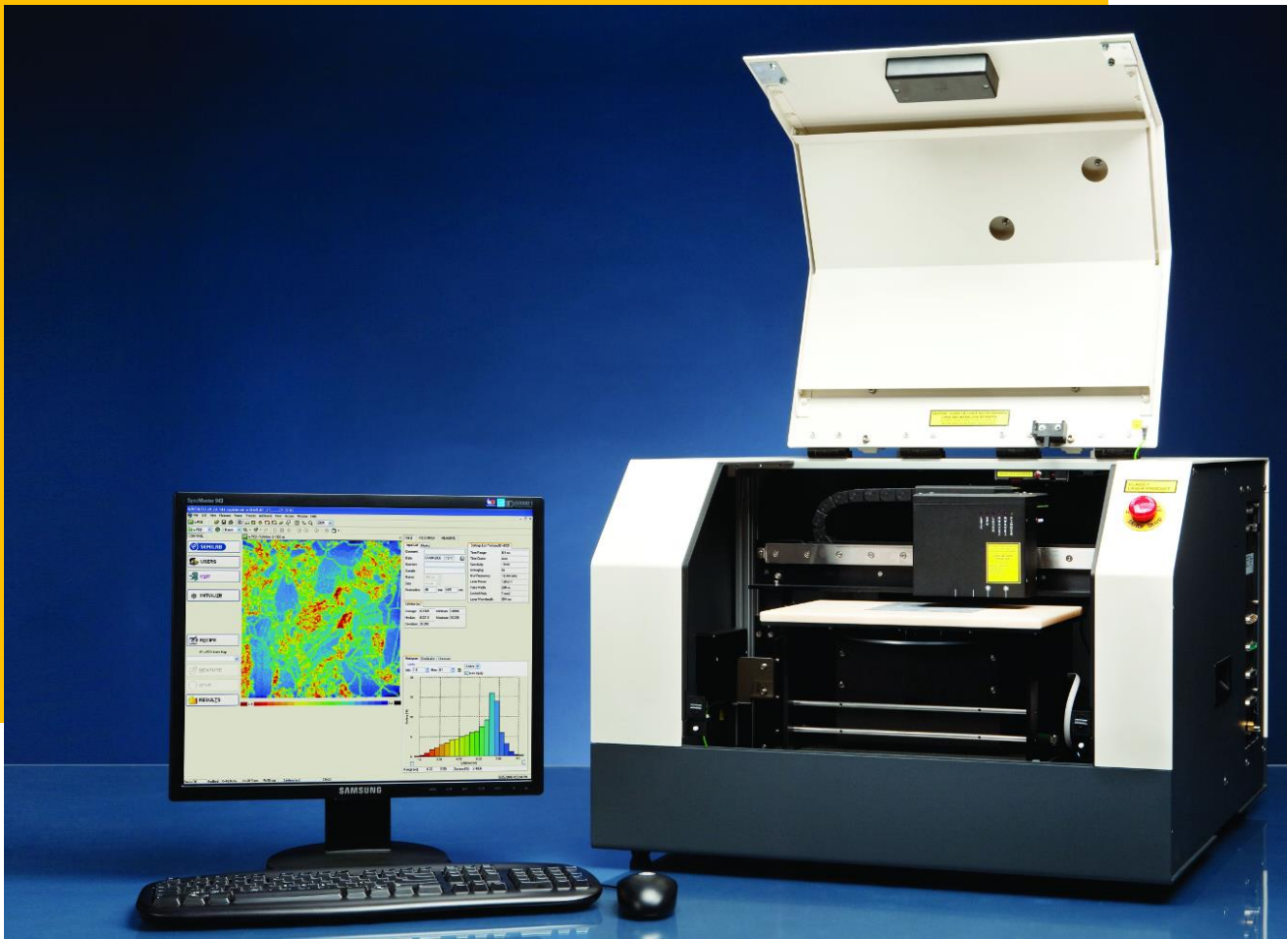


# LIGHT BEAM INDUCED CURRENT (LBIC)



## STANDARD OPERATING PROCEDURE (SOP) 2018 (v.1)



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# INTRODUCTION

WT-2000PVN system is equipped with a variety of measurements with mapping options including minority carrier lifetime, diffusion length, sheet resistance, current, quantum efficiency and reflectivity. However, Light Beam Induced Current measurement with mapping capability is possible at present.

## Light Beam Induced Current (LBIC)

LBIC (Light Beam Induced Current) option of the WT-2000PVN was developed specifically for PV applications. The measuring head includes up to four light sources with a spot size of 100  $\mu\text{m}$ . The system can measure the reflection of the cell, so the Internal Quantum Efficiency can be calculated for each wavelength. Using more than one wavelength, the Diffusion Length is calculated automatically. The Quantum Efficiency and Diffusion Length maps are characteristic of the quality of the solar cell. The LBIC measurement can be performed only on solar cells with shunt resistance at least 15  $\Omega$ .

## Equipment Configuration

The basic units with the system are

- WT-2000 main unit with scanning capability
- LBIC head with four lasers of wavelength (401, 658, 877, 988) nm.
- Sample stage
- Measuring computer (System 1, DOS) and User computer (System 2, Windows)
- Monitor, mouse, keyboard and a vacuum pump

## Software

The WT-2000 main unit is controlled by the WSOS2 software, which runs on the DOS (Measuring) computer. The Wintau32 software with the user-friendly interface runs on the Windows computer (User).

***“Got something very important to point out to your readers?  
Use this bar to make it stand out.”***

## System Installation

- Major components of equipment including DOS and WINDOW PC and Main unit shown below in Fig A.
- Main unit mainly consist the sample holding chuck and contact facility (back contact plate and front contact probe) with illumination and measurement facility (LBIC head) shown in Fig B. LBIC head is equipped with four different wavelength lasers and a detector, and attached with restring arm used for scan the sample during measurement.
- DOS PC is a computational unit and responsible for communication with main unit. (Fig C and D)
- WINDOW PC communicate with DOS PC and responsible for Input control and presentation of output results (Fig D).
- Fig E shows power supply connection for WINDOW & DOS PC and vacuum facility.

## Installed System

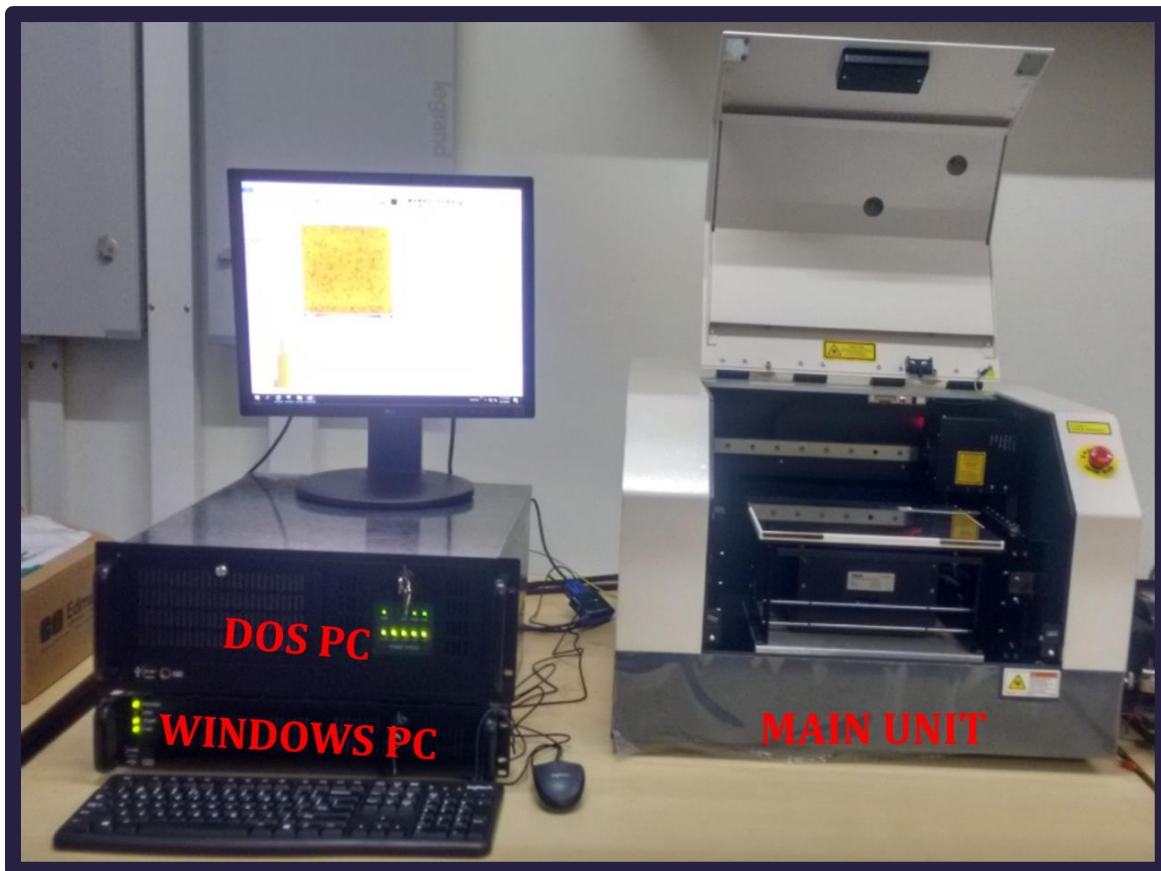


Fig A: Major units of equipment viz. main unit, DOS PC and WINDOW PC

## Main unit

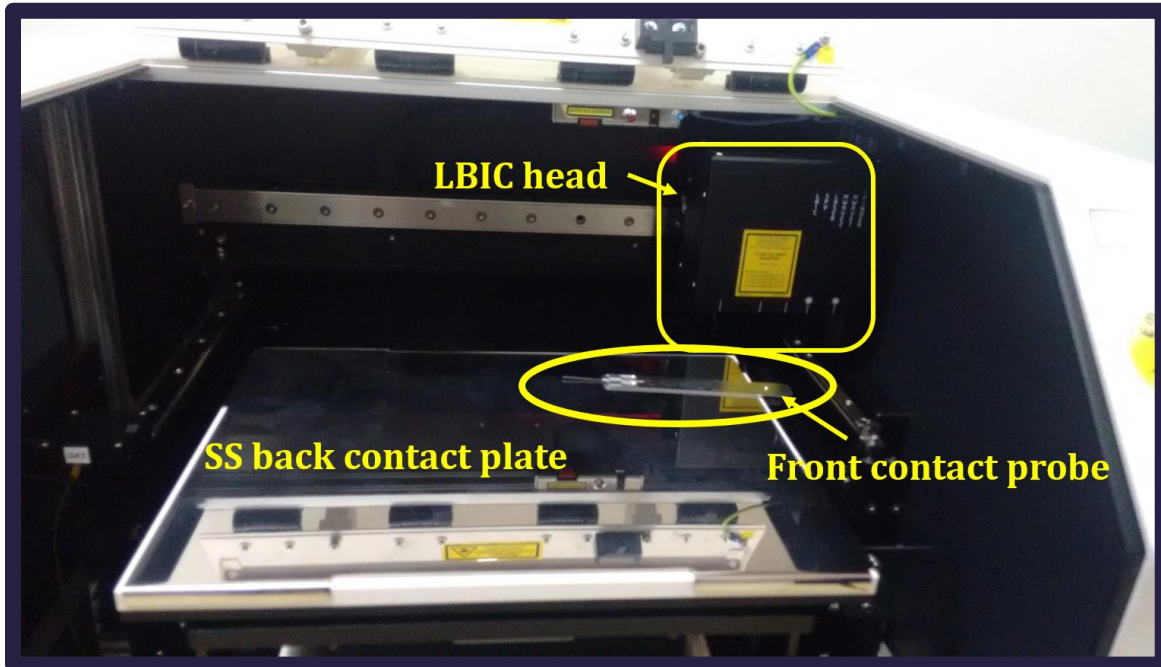


Fig B: Main unit consist of back contact plate (SS), front contact probe and LBIC head

## Connections associated with the Main unit

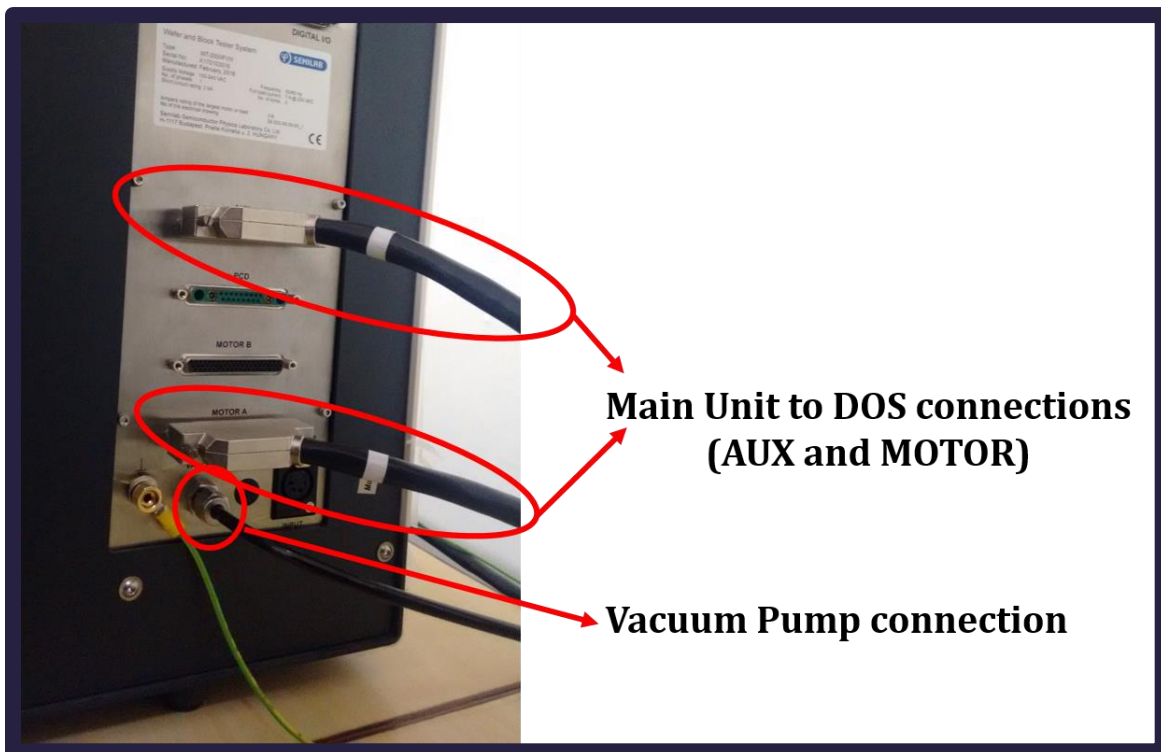


Fig C: Main unit communication to DOS PC and vacuum pump for sample holding



## Connections associated with the DOS PC

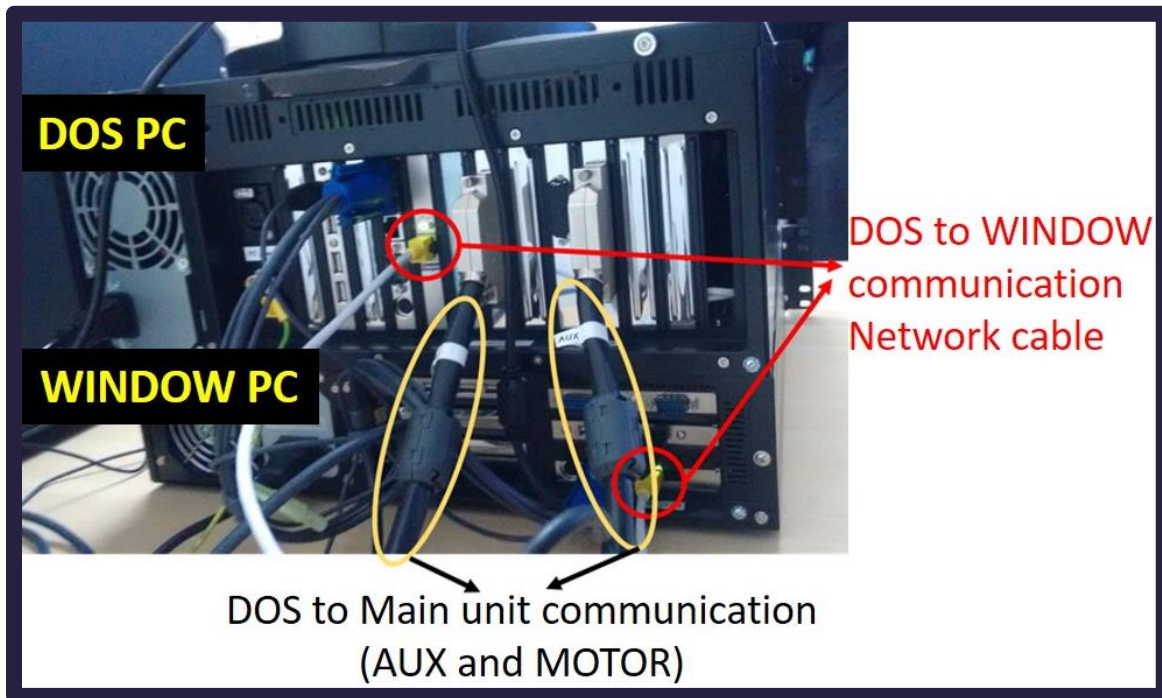


Fig D: DOS PC communication network with main unit and Window PC.

## Power Supply Connections

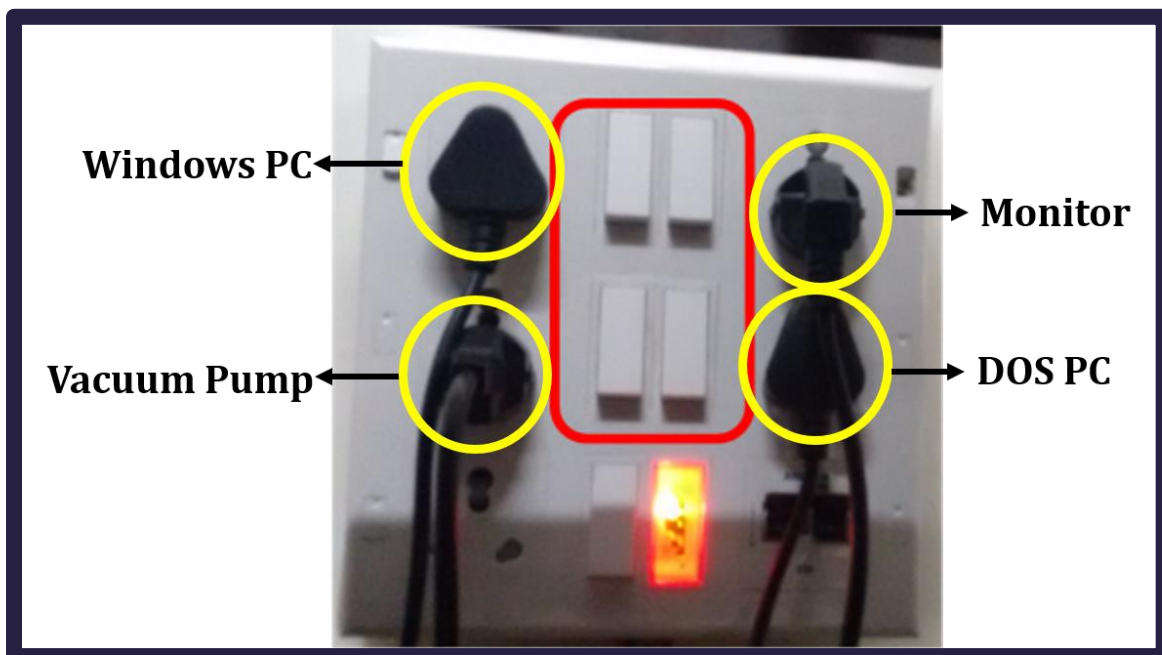






Fig E: Power supply to DOS & WINDOW PC, Monitor and vacuum pump.

# SAFETY PRECAUTIONS

The WT-2000 is designed to be completely safe when operated and maintained by properly trained personnel using procedures described by Semilab in the standard operating procedure.

## Safety Symbols

			
Ground Terminal	Electric shock hazard	Laser radiation hazard	Pinch point caution

## Safety Interlocks

- The access panel (door) is equipped with an interlock. The door may be opened during normal operation e.g. sample loading or unloading or even for maintenance purposes.
- The interlock override remains active until the next time the cover is closed. When the interlock is overridden, a red LED flashes continuously next to the override button, warning the user that laser triggering is enabled.
- LBIC units contain lasers that can emit visible and invisible laser radiation that may be harmful to human eyes. In these cases a warning label is mounted on the front panel and measuring head of the WT-2000 system.
- The moving parts can be stopped by hand force. If there is something in the way of a moving part that blocks the movement, the part stops, and the software gives an error message. After such an event, initialization is needed.
- Because of this, no serious injury is possible to be caused by the moving parts of the WT-2000. However, a warning label is placed on the inside bottom and outside front cover of the WT-2000 to prevent people from putting their limbs in the way.

- There is an Emergency Motor Stop switch on the front side of the main unit. Pressing the red knob turns off the power to all the motors of the system. It can be deactivated by turning the knob in a clockwise direction and releasing it. Once released, relaunch the software and proceed with normal operation.



**⚠ WARNING:** Do not view the flash directly. Do not operate the flash when the interlock is overridden. Do not remove the protective metal plates from the flash lamp.

**⚠ WARNING:** Do not view the laser directly. Do not inspect the laser with optical instruments such as a mirror or magnifier.



## CLEANING METHOD

- Cleaning procedures should be done with alcohol using lint-free cloth.
- Clean the rails directing the movement of the stage and the rail of the head.
- Dust can be removed from the not easily accessible parts by compressed air flow.
- The side covers can be removed by a 3 mm hex key. After cleaning, please make sure to reconnect grounding of all side covers.

**! CAUTION: Before removing a side cover always make sure that the equipment is switched off**

- The stage should be cleaned at the same time with a dry cloth.

**! CAUTION: Do not clean the ESD table with alcohol or any other solver!**

- It is advised to lubricate the rail of measurement head, measurement stage, bridge, loading arm and the bearing of indexer (can be reached when indexer platform at lower position) once a year, or if the movement produces noise. Loading arm and indexer are only present in equipment with automatic loading option (Fig F).

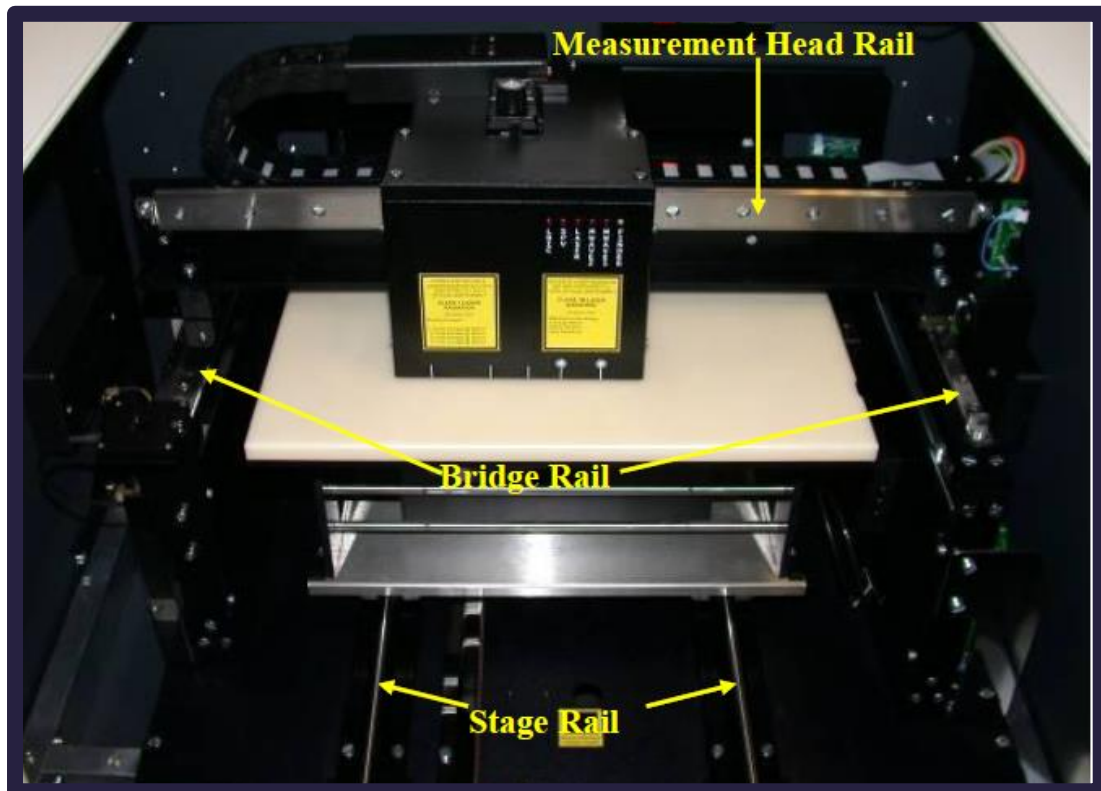
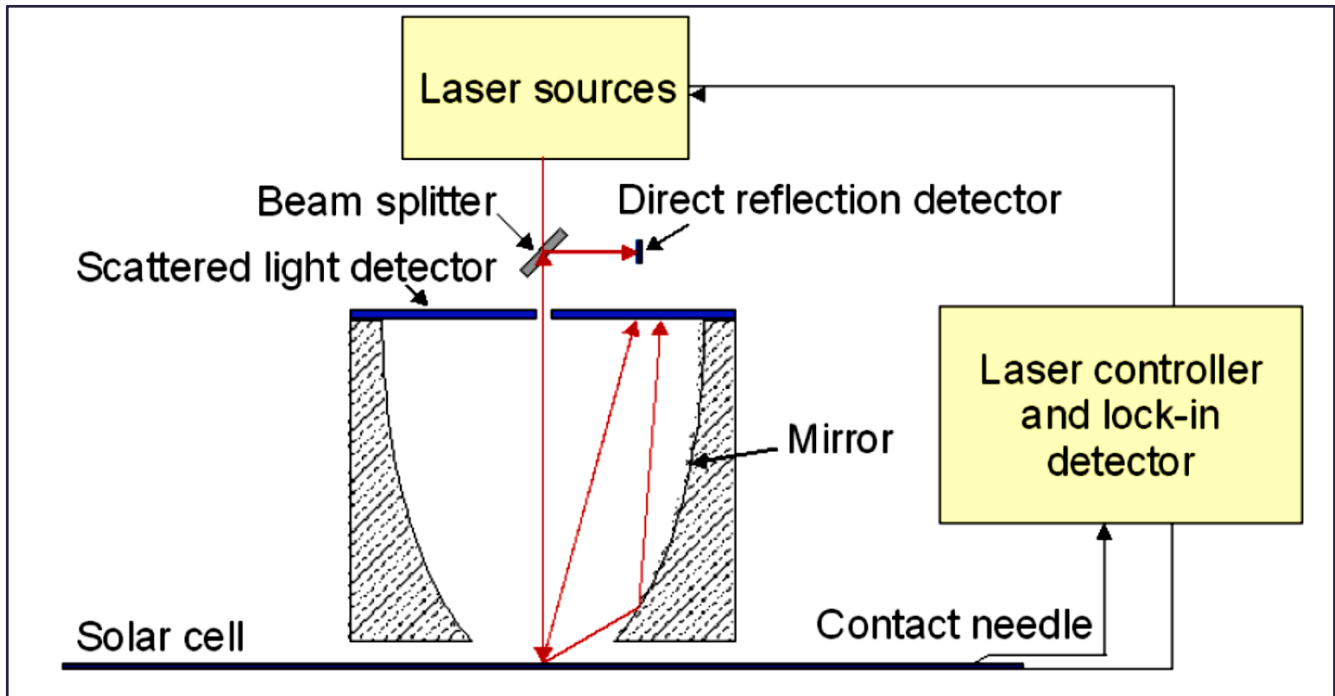


Fig F: Important mechanical movements should be lubricate.

# OPERATION THEORY (LBIC)

## Reflection Measurement and IQE Calculation

The total reflection from the cell consists of two parts: direct and scattered reflectance. The scattered reflection is collected by an ellipsoid mirror and a silicon detector shown in figure below. Both reflectance parts are calibrated to a reflection standard.



Knowing the light flux ( $\Phi$ ) and the total reflectance  $R$ , the Internal Quantum Efficiency can be calculated from the measured short circuit current ( $I_{sc}$ ):

$$IQE = \frac{1}{(1 - R)} \frac{I_{sc}}{\Phi \cdot q} \quad \dots(1)$$

## Diffusion Length Calculation

The diffusion length can be calculated if more than one wavelength is used during the measurement. Solving the diffusion equation and assuming that the back surface recombination velocity ( $S_b$ ) is high, the relationship between  $I_{sc}$  (short circuit current) and the number of penetrated photons (light flux,  $\Phi_A$ ) can be written as follows:

$$IQE = \frac{I_{SC}}{\Phi_A \cdot q} = 1 - e^{-\alpha w} + \frac{\alpha L e^{-\alpha w}}{(\alpha L)^2 - 1} \left\{ \alpha L - \frac{\left[ \cosh\left(\frac{t-w}{L}\right) - e^{-\alpha(t-w)} \right]}{\sinh\left(\frac{t-w}{L}\right)} \right\} \dots(2)$$

where L is the diffusion length,  $\alpha$  is the absorption coefficient of the light ( $1/\alpha$  is the penetration depth), w is the space charge width, t is the cell thickness, and q is the charge of the electron. We can simplify this equation by using several different approximations.

$$e^{-\alpha w} \approx 1 \quad \text{if} \quad w \ll \frac{1}{\alpha} \dots(3)$$

Eq. (3) stated that the penetration depth of the light should be much higher than the space charge region. This implies that we should use infrared lasers for diffusion length calculation.

$$e^{-\alpha(t-w)} \approx 0 \quad \text{if} \quad t - w \gg \frac{1}{\alpha} \dots(4)$$

Because  $t - w \approx t$  in the case of a standard solar cell, the penetration depth of the light should be less than the sample thickness.

$$\frac{\cosh\left(\frac{t-w}{L}\right)}{\sinh\left(\frac{t-w}{L}\right)} \approx 1 \quad \text{if} \quad t - w > 3 \cdot L \dots(5)$$

**The diffusion length should be less than one-third of the sample thickness.**

Using the approximations in equations (3) through (5) in the original equation (2), we get:

$$IQE = \frac{\alpha L}{(\alpha L)^2 - 1} (\alpha L - 1), \quad \text{OR} \quad \frac{1}{IQE} = \frac{\alpha L + 1}{\alpha L} = \left( 1 + \frac{1}{\alpha} \cdot \frac{1}{L} \right) \dots(6)$$

If we plot  $\Phi/I_{SC} = IQE \cdot q$  as a function of the penetration depth  $1/\alpha$ , we get a linear plot. The intercept with the X-axis is the diffusion length L:

$$0 = \frac{1}{IQE} = \left( 1 + \frac{1}{\alpha} \cdot \frac{1}{L} \right) \dots(7)$$

$$L = -\frac{1}{\alpha} \quad \dots(8)$$

The equations and the limitations are very similar to the Surface Photovoltage (SPV) method of measuring diffusion length.

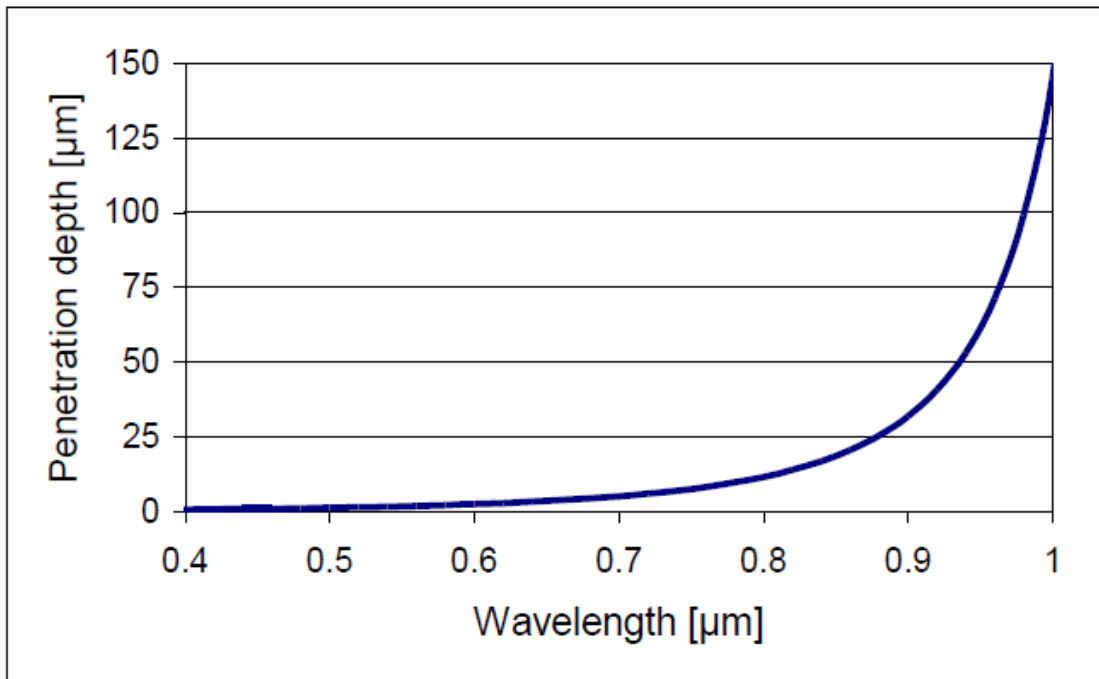
### Absorption coefficient and Penetration depth for different wavelengths

Diffusion length calculation needs the penetration depth value for each wavelength. The software uses the following equation to calculate the absorption coefficient in the case of perpendicular light beam:

$$\alpha = \left( \frac{84.732}{\lambda} - 76.417 \right)^2 \quad \dots (9)$$

where  $\lambda$  is the wavelength in  $\mu\text{m}$  and the absorption coefficient  $\alpha$  in  $\text{cm}^{-1}$  units.

The penetration depth ( $1/\alpha$ ) curve plot according to the above equation can be seen in the figure below:



**Table: Penetration depth of standard LBIC lasers**

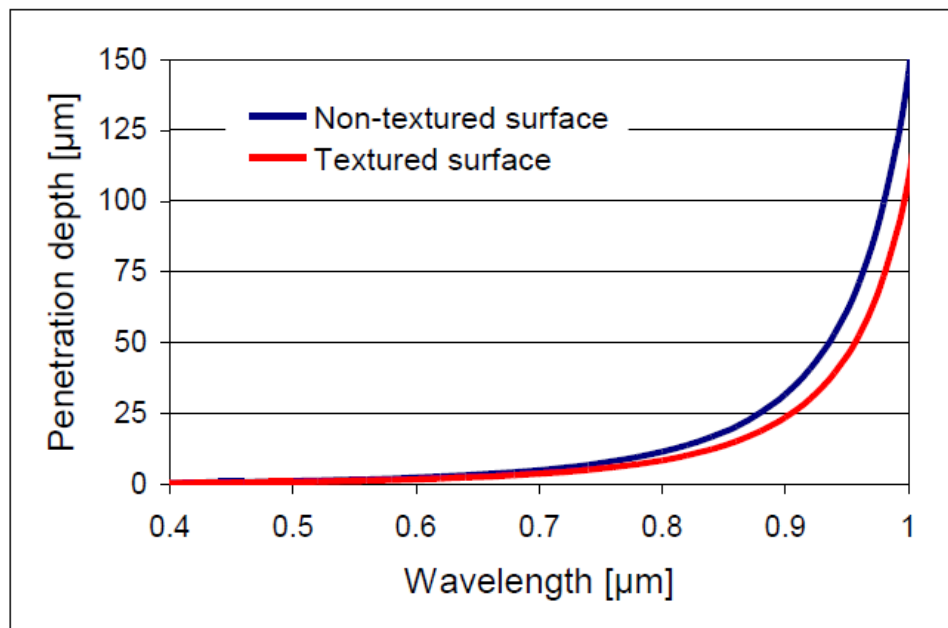
Wavelength (nm)	Penetration Depth ( $\mu\text{m}$ )
1015*	199
980	99
950	61
880	25
850	18
650*	3.4
405*	0.5

\*Not recommended for diffusion length measurement of traditional Si solar cells

### Influence of the Textured Surface in Penetration depth and Diffusion Length Calculation

The solar cell performance can be increased by texturing the surface. Using anisotropic etch randomly placed and sized pyramids (1-3  $\mu\text{m}$ ) can be formed on the surface. A textured surface has two advantages for cell performance: 1) reduces reflection losses by multiple incidence and 2) it allows non-perpendicular paths for the light, thus electron-hole pair generation takes place closer to the surface and increase the efficiency especially for longer wavelength light. *The effect is similar to that increasing the absorption coefficient by 1.35 compared to the non-textured surface.* The penetration depth value is shortened by this number, so the calculated diffusion length is overestimated compared to the bulk diffusion length. The real diffusion length can be achieved by multiplying the fitted value with 0.74.

Figure shown below, illustrates the shortening of the penetration depth in the case of a textured surface.



### Limitation of Sample thickness when measuring Long Diffusion Length

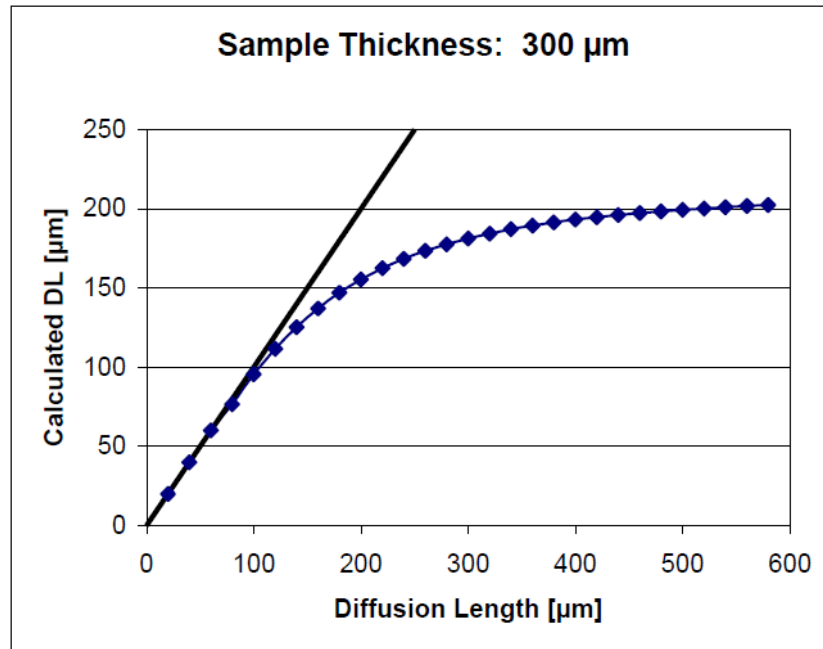
In [Diffusion Length Calculation](#) section, we made three assumptions [equations (3), (4), and (5)] about the geometry of the cell and the wavelength of light sources. The first two can be fulfilled by careful wavelength selection; equation (3) eliminates the short wavelengths and (4) the long wavelengths. The third equation (5) includes an assumption about the sample thickness and the diffusion length. The standard solar cell thickness is usually in the 150 - 300  $\mu\text{m}$  range, so it means that the diffusion length calculation is correct up to about 100  $\mu\text{m}$ .

At thicknesses of less than 100  $\mu\text{m}$ , equation (3) is not fulfilled and the diffusion length calculation is not valid. Let us see what happens when we still use the plot from equation (6) for diffusion length calculation.

Assuming (3) and (4) and leaving out the assumption (5), the equation (2) can be written as follows:

$$\frac{1}{IQE} = \frac{L^2 - \frac{1}{\alpha^2}}{L^2 - \frac{L}{\alpha \cdot \tanh(t/L)}} \quad \dots (10)$$

If we plot the fitted diffusion as a function of the real bulk diffusion length the result will be shown in Figure below





It is clear from the graph shown above that the fitting to the LBIC plot will underestimate the bulk diffusion length. The exact shape of the curve may be different from the above if the recombination velocity is not high at the back surface. To be able to compensate for this effect, the back surface recombination velocity has to be known.

## References

- Hovel, H.J. Solar Cells. In Semiconductors and Semimetals, Vol. 11, edited by R.K. Willardson and A. C. Beers. New York: Academic Press, 1975:16-19.
- Schroder, Dieter K. Semiconductor Material and Device Characterization. New York: Wiley, 1990:381.
- Green, M.A. High Efficiency Silicon Solar Cells. Aedermannsdorf: Trans Tech Publications, 1987:144.

# STANDARD OPERATING PROCEDURE

## Section 1.1: Switching On

1. Switch on the main power supply. ( All 4 switches Figure. 1 (a))
2. Turn on the windows PC (Figure. 1 (b)) and wait for 30 seconds.
3. Turn on the DOS PC (Figure.1 (b)) and wait for 1 min.

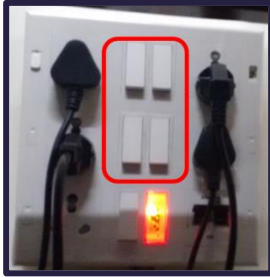


Figure.1 (a)

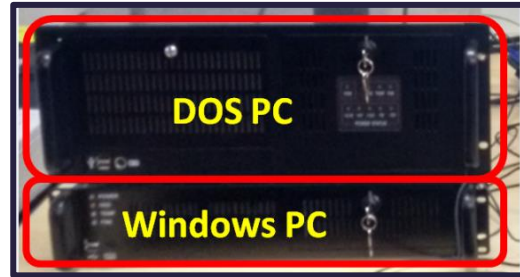


Figure. 1 (b)

4. Launch the software "Wintau32".

**Note:** Wait until the status bar shows "WS7.82 OK"

5. Initialize the software by clicking "INITIALIZE" menu. This step is required only when DOS has been restarted.

**Note:** Wait until the status bar shows "WS7.82 OK". (Figure. 2)

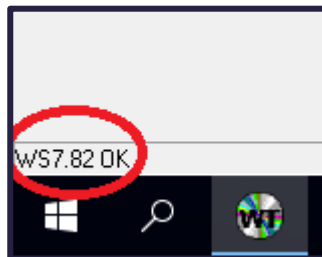


Figure. 2

## Section 1.2: Measurement settings

6. Click on "Measurement Options" tab.
  - a. In "Loading" option, set "Wafer Shape" and "Wafer Size" as per your sample requirement. (Figure. 3)
  - b. In "Single" option, set "Number of Points" as per requirement. (Figure. 4)
  - c. In "Auto" option, select "Measurement Type" (Points/Map) and click on "Apply" and then "OK" button. (Figure. 5)

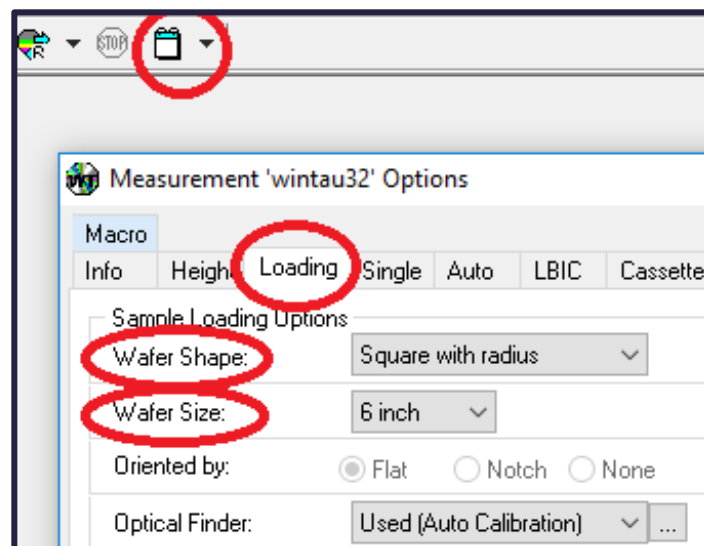


Figure. 3

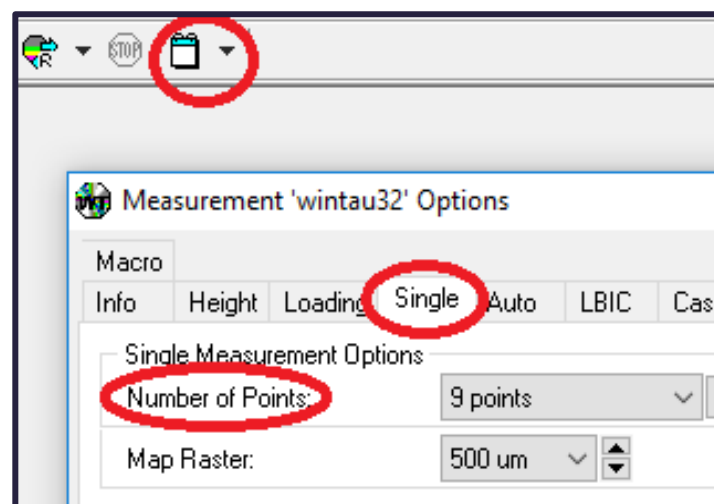


Figure. 4

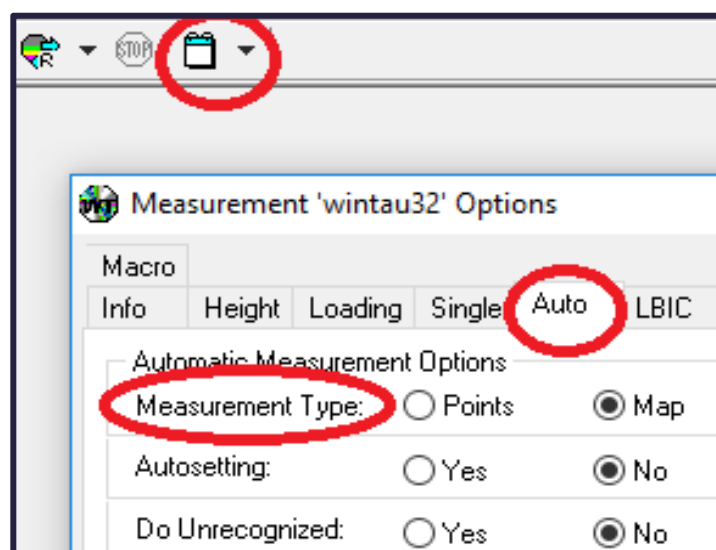


Figure. 5

7. Check the scanning parameter window in the right hand side of the screen. (Figure. 6)

INFO RECORDER MEASURE ALARM

Input List: Masks

Comment:

Date: 5/31/2018 17:56

Operator:

Sample:

Raster: 500 um

Size: 6 inch

Scanradius: 75 mm 75 mm

Figure. 6

- In "INFO" tab, select the "Raster" size as per the requirements.
- In "RECORDER" tab, choose the "Isc", "Rd" and "Rsc" corresponding to the wavelength specified. (Figure. 7)

INFO **RECORDER** MEASURE ALARM

Settings

Diff. Length: NA

Regression: -0.33974

Averaging: 8

Frequency: 0.4 kHz

☒ Textured

Range: 5000

LBIC Plot

GF lux/LBIC

Penetration Depth [um]

Update

Lasers Settings

			Isc	Rd	Rsc
984 nm	<input type="text"/>	5.000 V	<input checked="" type="checkbox"/> 0.03 uA	<input checked="" type="checkbox"/> 2.70%	<input checked="" type="checkbox"/> 6.23%
877 nm	<input type="text"/>	5.000 V	<input checked="" type="checkbox"/> 0.03 uA	<input checked="" type="checkbox"/> 8.68%	<input checked="" type="checkbox"/> 3.54%
658 nm	<input type="text"/>	5.000 V	<input checked="" type="checkbox"/> 0.03 uA	<input checked="" type="checkbox"/> 3.02%	<input checked="" type="checkbox"/> 4.52%
407 nm	<input type="text"/>	5.000 V	<input checked="" type="checkbox"/> 0.03 uA	<input checked="" type="checkbox"/> 3.55%	<input checked="" type="checkbox"/> 0.64%

Head Height: 6.765 mm Temperature: 26.4 C

Figure. 7

### Section 1.3: Sample Loading

8. Click on “Load wafer” tab for loading the sample. (Figure. 8)

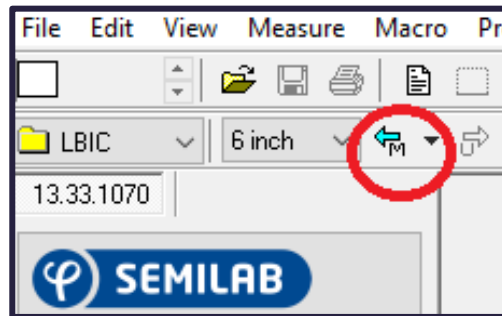


Figure. 8

9. Open the lid of the measuring system. (Figure. 9)

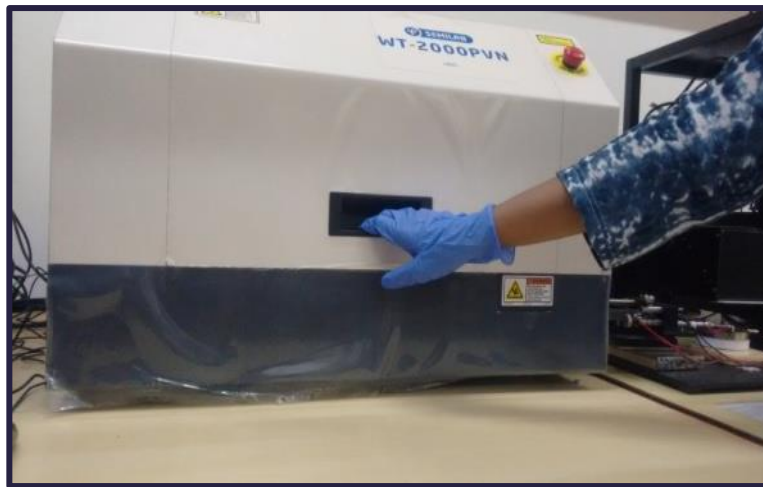


Figure. 9

10. Load the wafer on to the chuck. (Figure. 10)

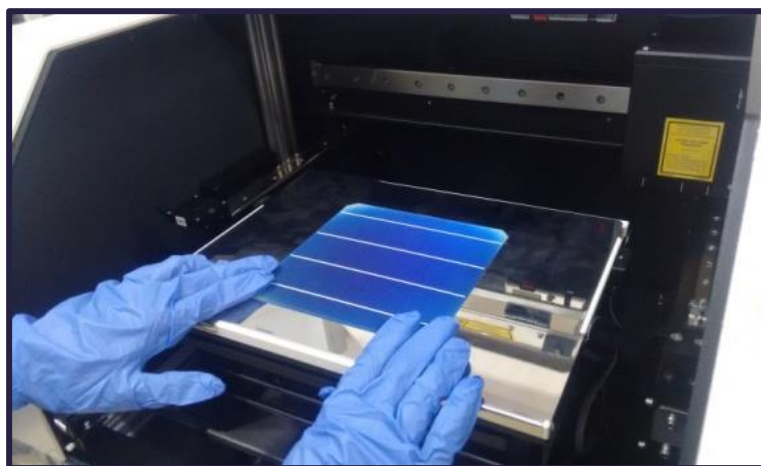
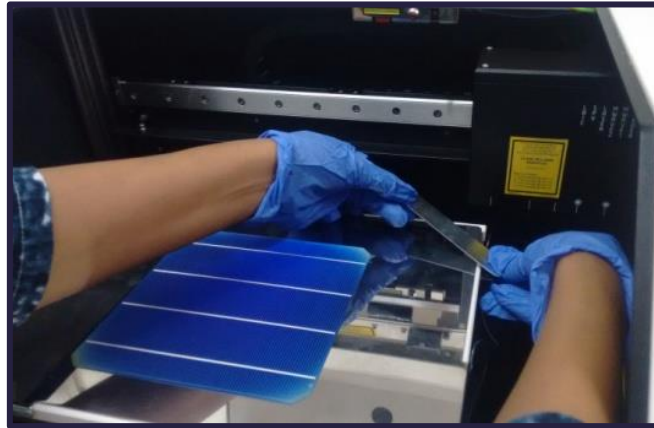


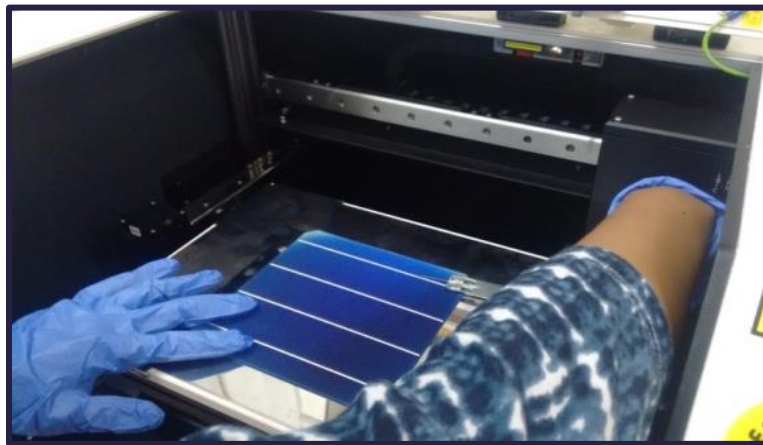
Figure. 10

**11.** Connect the contact probe. (Figure. 11)



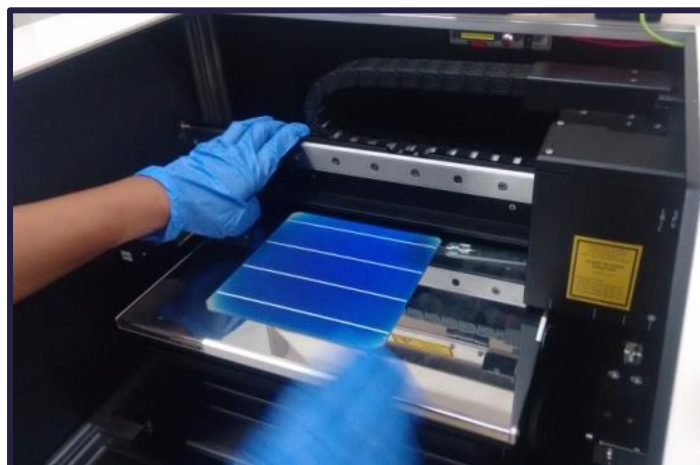
**Figure. 11**

**12.** Probe the sample using contact probe. (Figure. 12)



**Figure. 12**

**13.** Check the wafer alignment with the help of bridge connected to the LBIC head.  
(Figure. 13)



**Figure. 13**



14. Close the lid and then press “Vacuum On” and “OK” in Load Sample pop up. This would scan the wafer for its boundaries. (Figure. 14)

**Note:** Wait until the status bar shows “WS7.82 OK”.

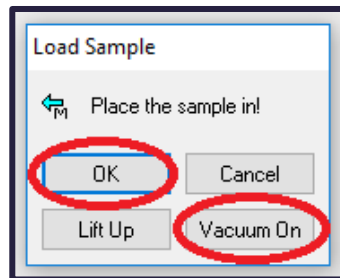


Figure. 14

### Section 1.4: Measurement

15. Start the measurement by clicking on the “MAP” tab. (Figure. 15)

**Set the measurement path in your respective folder in “USER DATA” folder in C:drive where you want to save the generated “.slf” file. Once the measurement path is saved, the measurement starts automatically. (Fig. 15)**

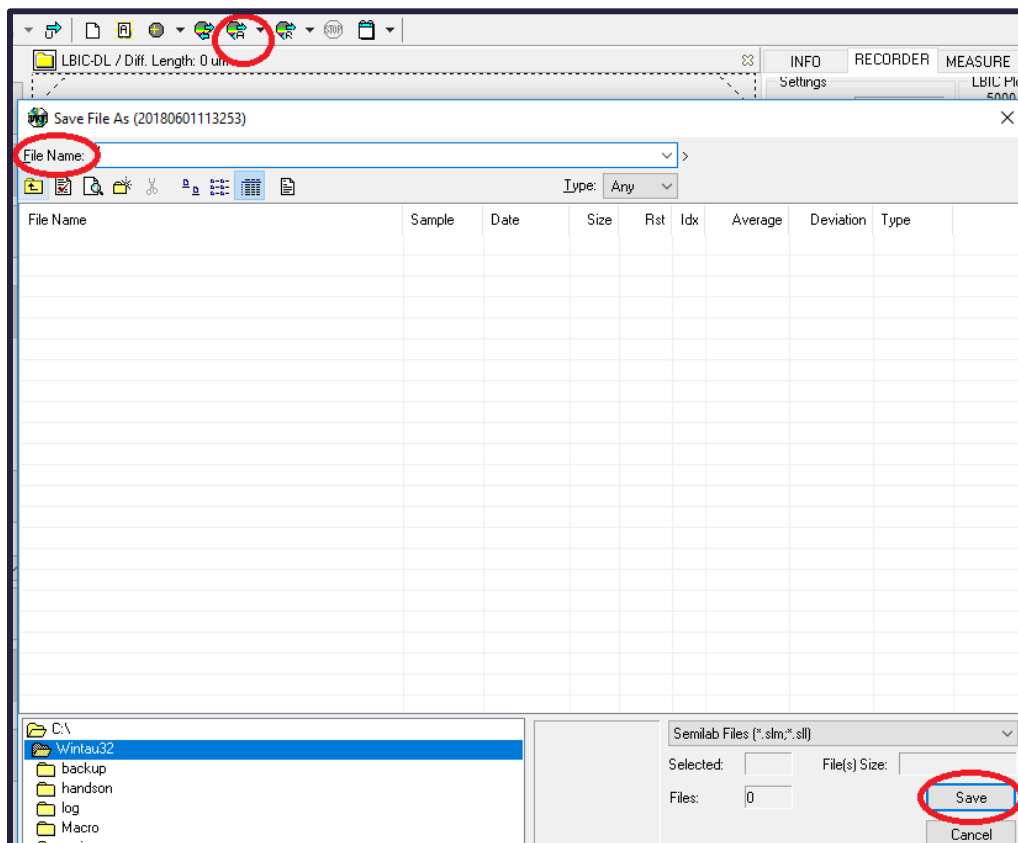


Figure. 15

16. Wait until the measurement completes. Time required for the measurement can be seen on status bar. (Figure. 16)

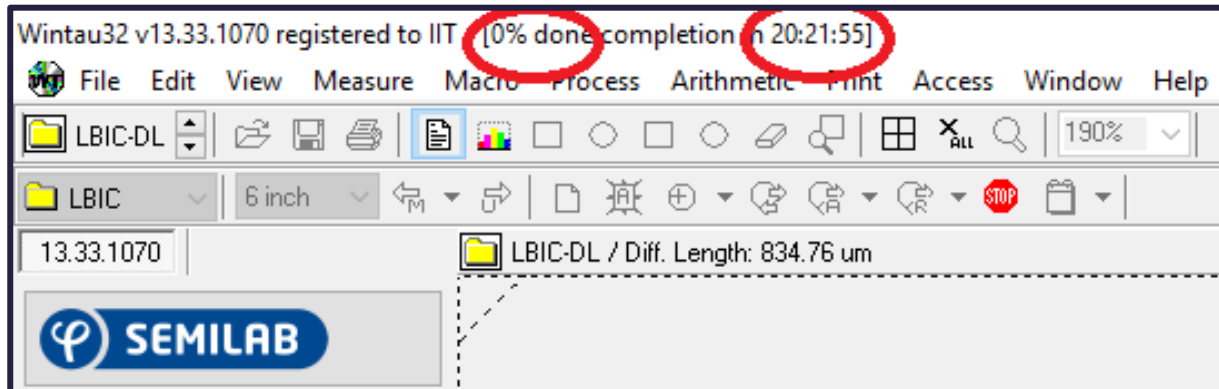


Figure. 16

### Section 1.5: Sample Unloading

17. Click "Unload wafer" tab for unloading the sample. (Figure. 17)

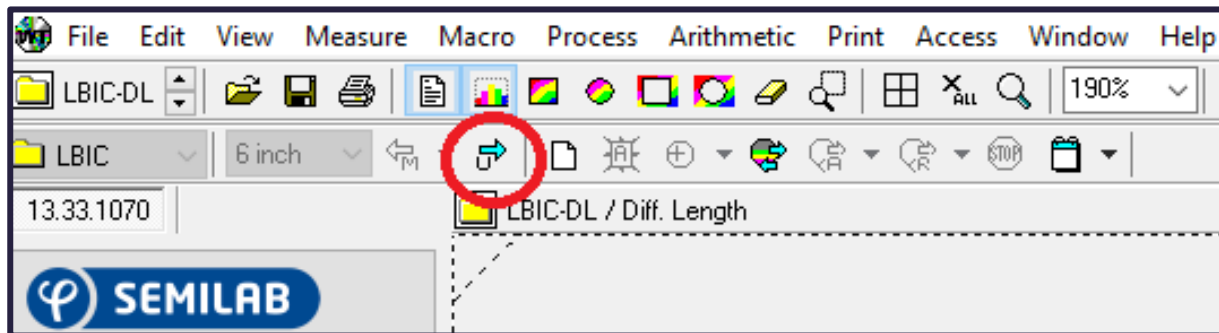


Figure. 17

18. Open the shutter by pulling the lid
- Un-probe the sample using contact probe.
  - Unload the wafer from the chuck.
  - Disconnect the contact probe.
  - Close the lid and then click "OK" in the "Unload Sample" popup.  
(See the Figure. 18)

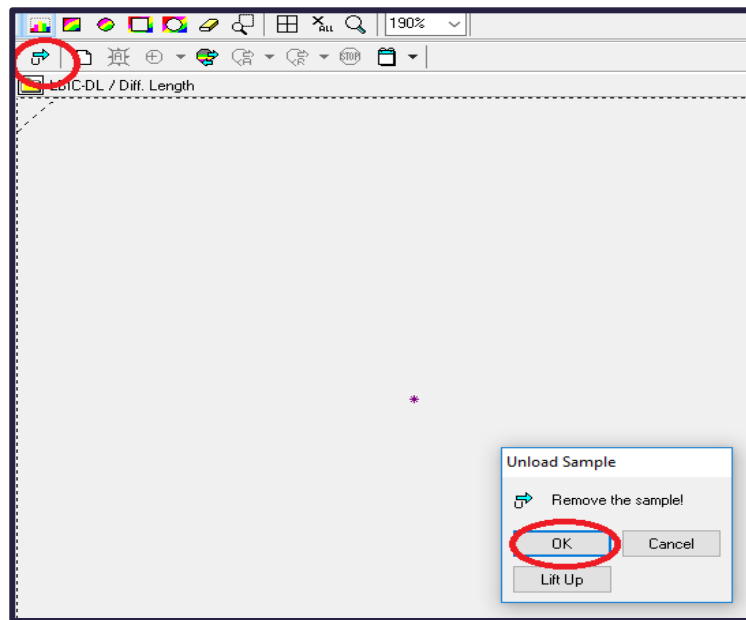


Figure. 18

## Section 1.6: EQE and IQE Mapping

19. Open the .slf file by clicking *File/Open/folder/LNK* type file. (Figure. 19)

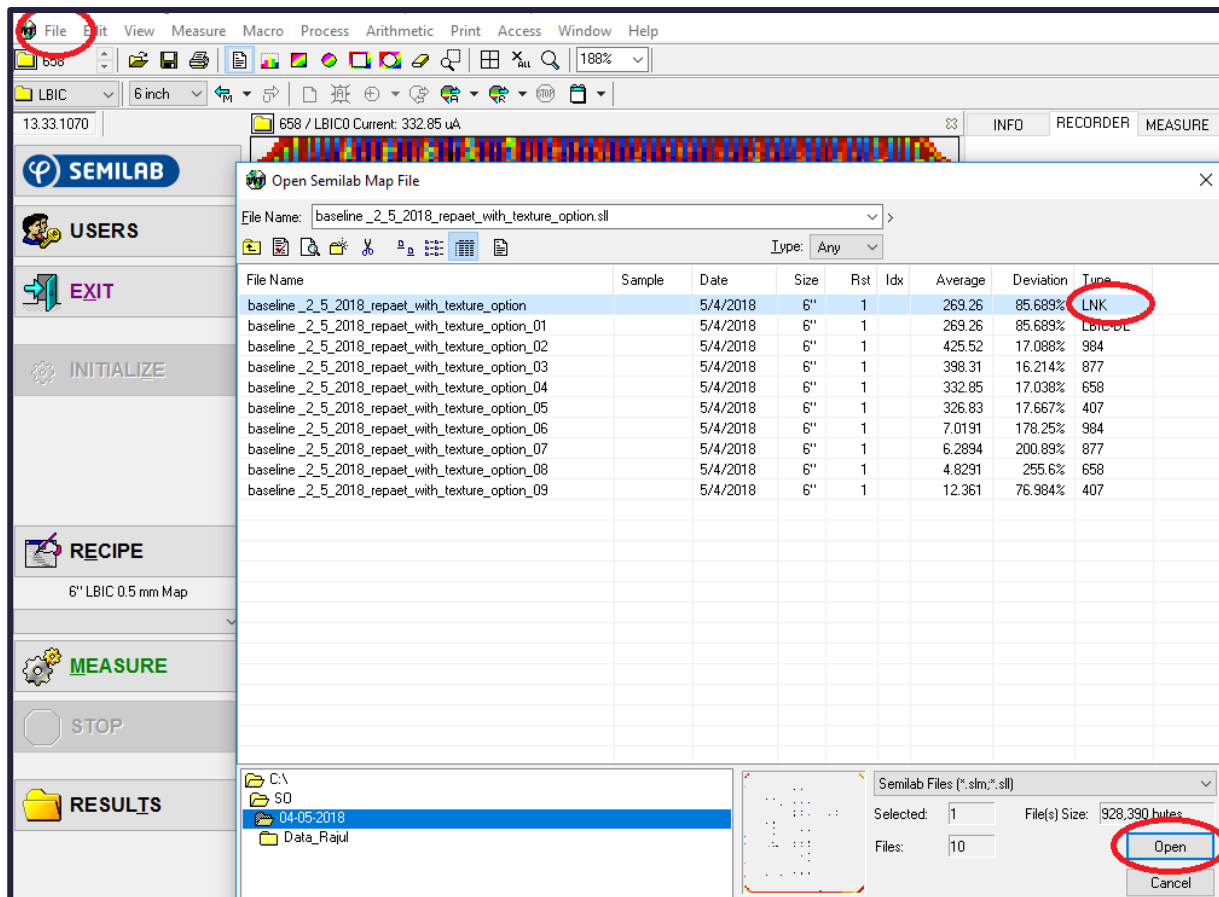


Figure. 19

20. Go to “ARITHMETIC” menu and choose “External Quantum Efficiency” or “Internal Quantum Efficiency”. (Figure. 20)

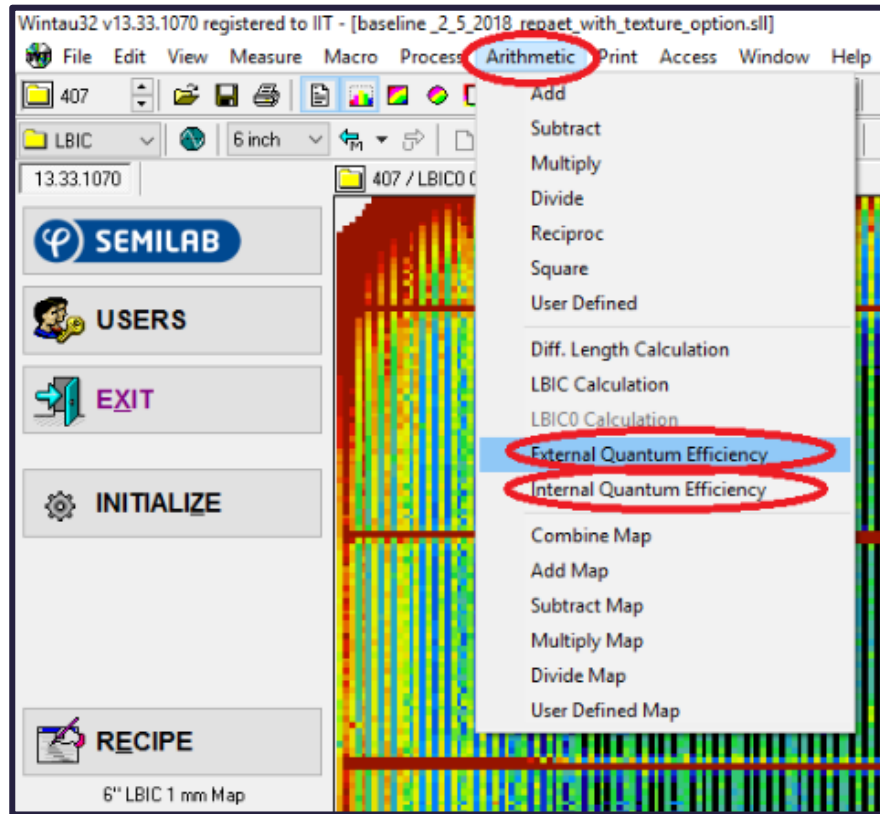


Figure. 20

21. Click “OK” in the “Quantum Efficiency Calculation” pop-up window. (Figure. 21) **Note:** Once EQE/IQE has been calculated, Isc maps are replaced by QE maps.

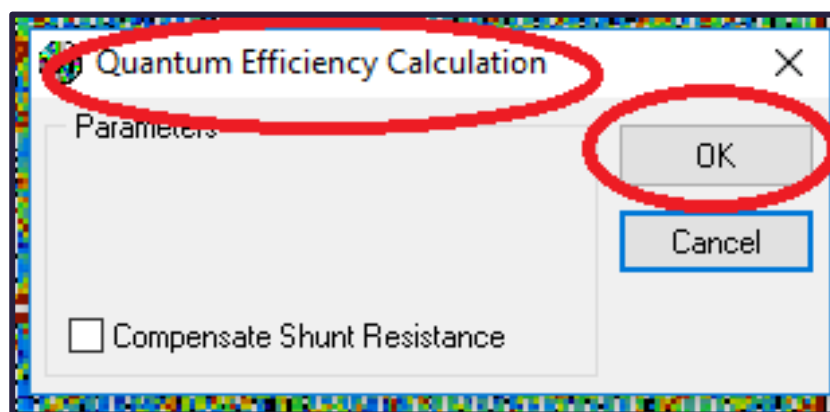


Figure. 21

## Section 1.7: Saving maps and corresponding data

22. Can save the map and histogram by clicking “File/Export bit map”. (Figure. 22)

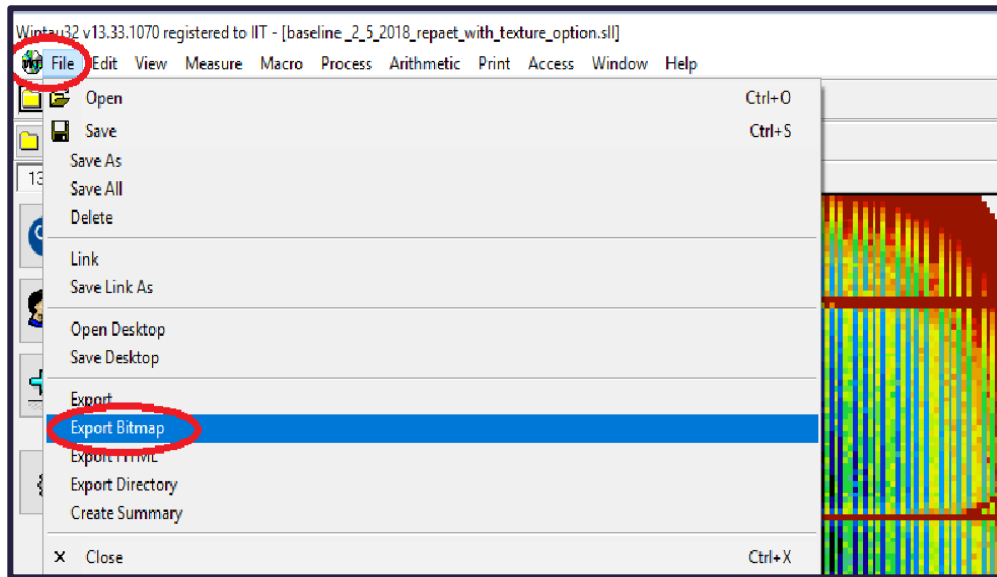


Figure. 22

23. The data points of the map can be extracted by clicking “File/Export”. (Figure. 23)

**Note:** A bitmap file of the map and note pad comprising of the data at the corresponding wavelength would be automatically saved in folder specified in the section 1.4 (step no. 15)

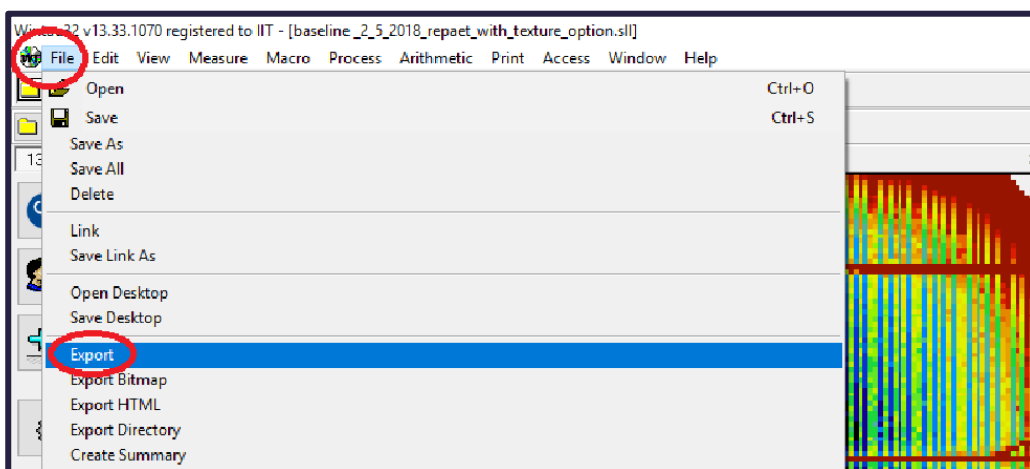


Figure. 23

## Section 1.8: Reflectance measurement only

**Note: Use SS plate only for reflectance mapping of low reflective (saw damaged removed (SDR), textured and antireflection deposited) samples.**

Follow the same procedure as described in section 1.1, section 1.2, section 1.3, section 1.4, section 1.5. Only changes are to be made in following steps:

24. In Section 1.2 (Measurement Settings) [7 (a) & (b)], select “Rd” and “Rsc” and deselect “Isc” in the scanning parameter window for desired wavelengths.
25. In section 1.3 (Sample loading), skip step 11 and step no. 12 to connect the probe and make contact via probe.
26. In Section 1.5 (Sample Unloading), skip step no. 18 (a) – (c) only.

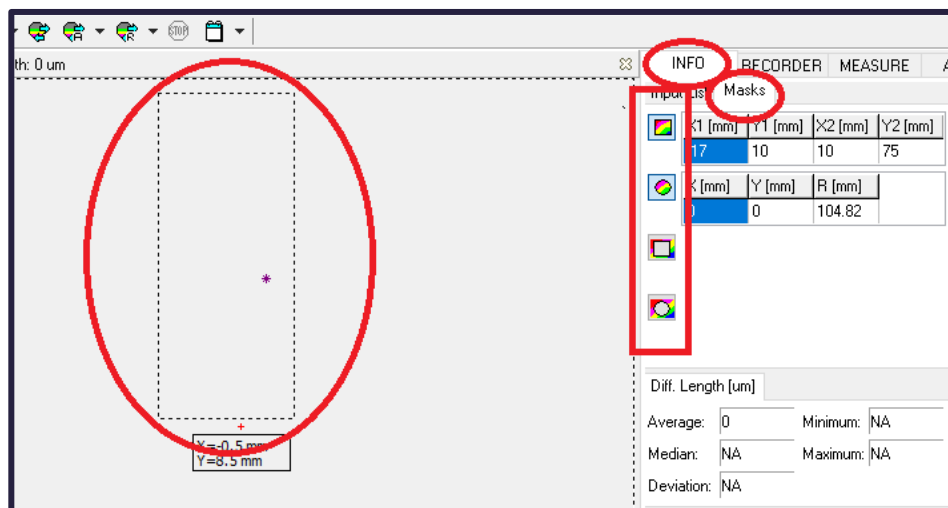
## Section 1.9: Measurement under mask

Follow the same procedure as described above in section 1.1, section 1.2, section 1.3, section 1.4, section 1.5, section 1.5. Only changes are to be made in following steps:

27. In section 1.2, not to choose “Square with radius” in “Wafer Shape” option (see Fig. 3).
28. Load your wafer as discussed in section 1.3 and 1.8.
29. Before starting the measurement, choose your desired mask in the “INFO” section of scanning parameter window. (Figure. 24)

**Note:**

- a. Dimensions of the mask can be adjusted in the same window.
- b. The mask can be deselected by clicking the option once again.



**Figure. 24**

30. Follow section 1.4 for the measurement.



## Section 1.10: Switching Off

31. Close the software by clicking “EXIT” menu. (Figure. 25)

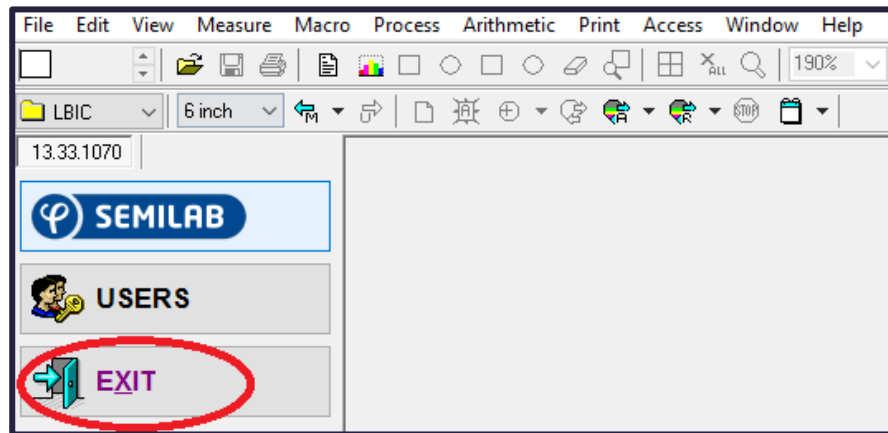


Figure. 25

32. Close all the tabs, open in the system and then shut down the Windows PC.

33. Turn off the DOS PC.

34. Switch off all the main power supply (4 switches).

# CALIBRATION OF REFLECTION (FOR SO's ONLY)

## LBIC Calibration :

The intensity of the lasers (flux) has to be calibrated for proper measurements. Calibration should be done twice a year. During the calibration the system measures the photodiode current.

➤ Flux intensity calibration can be done by using following steps:

**Note** : Only do calibration after the warm-up time of the system

1. Go to LBIC recorder window.
2. Right click and select "Calibration"->"Flux" as shown in Figure. 26

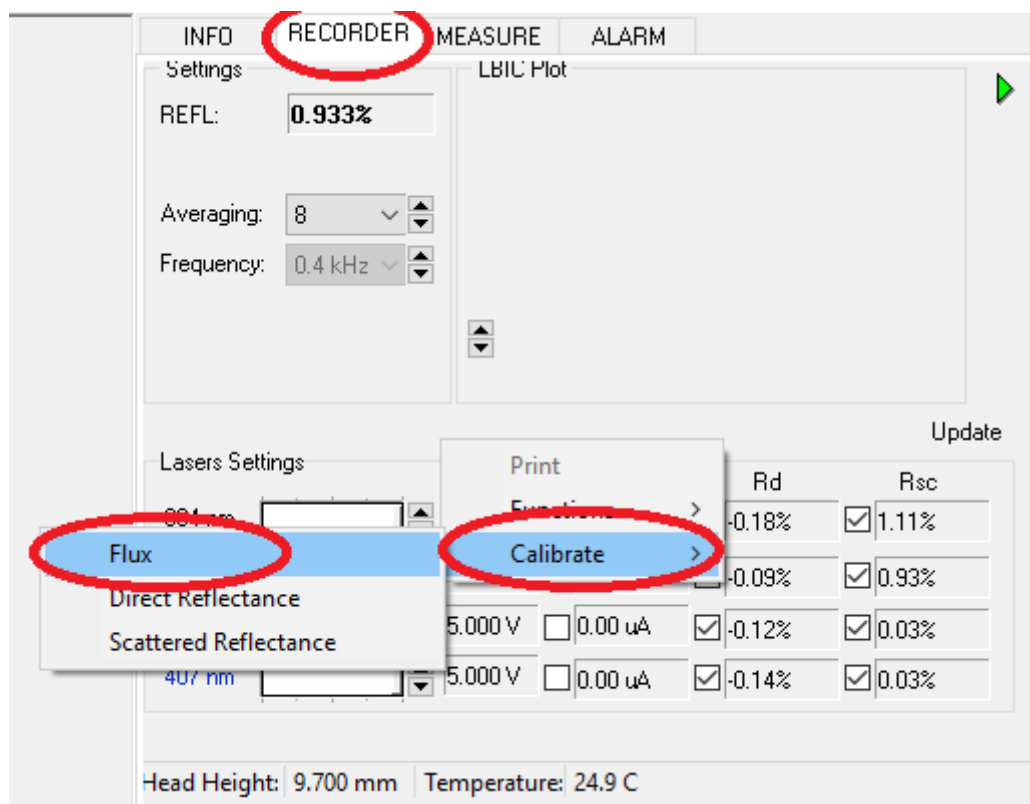


Figure. 26

3. Right click and select "Functions" -> "Calibration Curves" to check the calibration result i.e. Gflux versus DA value as shown in figure. 27 and figure. 28 (**DA value is LBIC power of laser** and Gflux is the calculated flux/intensity in  $10^9$  photons/s)

**Note:** Gflux versus DA value. Should be linear for proper operation.

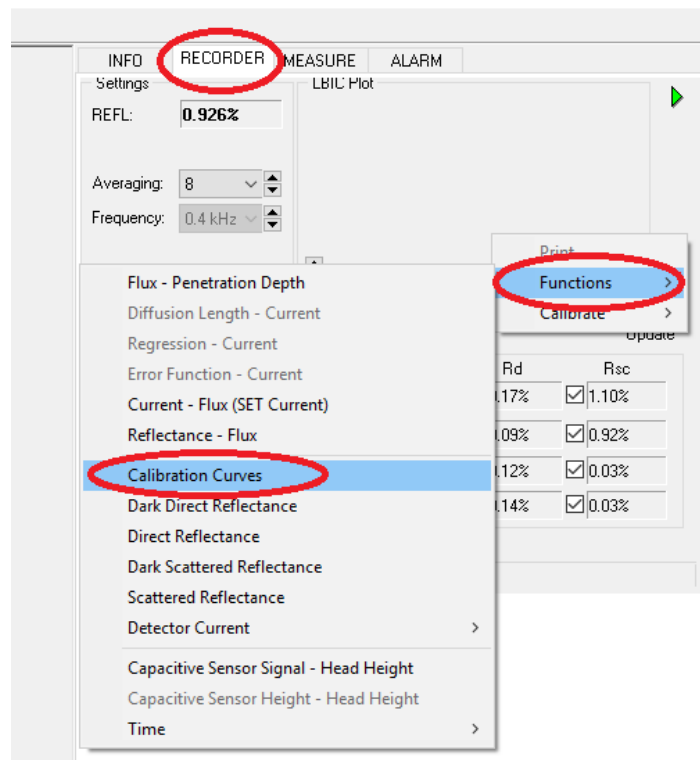


Figure. 27



Figure. 28

# EQUIPMENT MAINTENANCE WORKSHEET

## (FOR SO's ONLY)

Sr. NO	Date	People involved	Action	Remarks

Sr. NO	Date	People involved	Action	Remarks