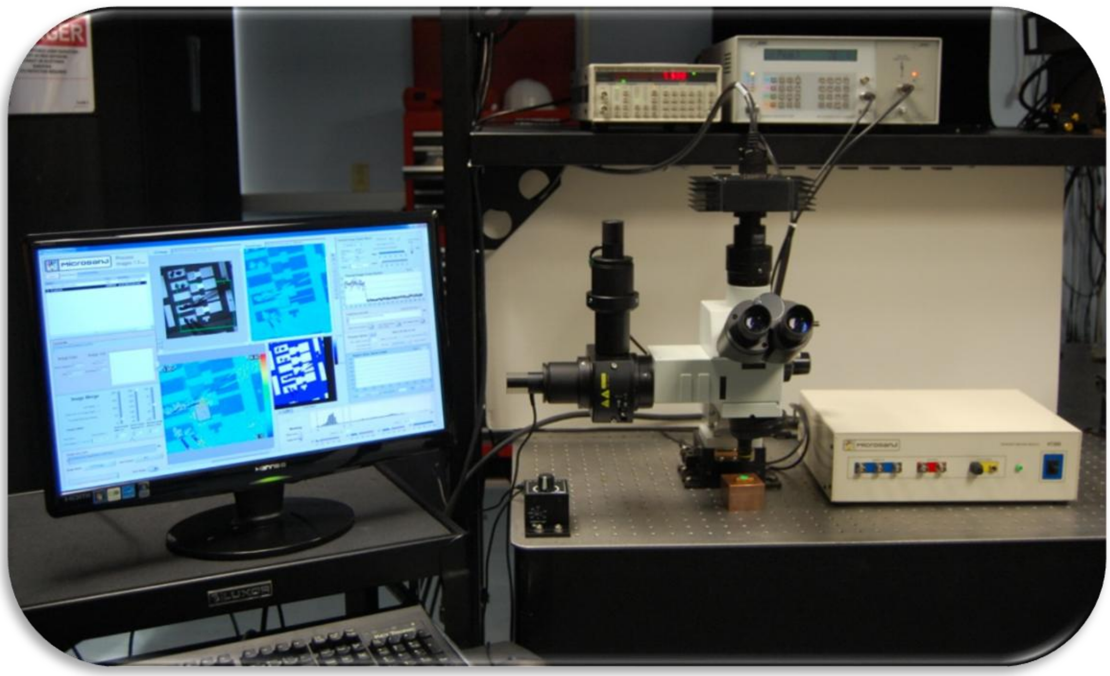
MicrosanJ

Technical Reference



NT200t

Transient Thermal Imaging

Microsanj LLC
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Congratulations!

The NT200t is the world's first commercially available transient thermoreflectance imaging analyzer, and is the only thermal imaging system with resolution to 100 nanoseconds. This, combined with the 0.2C thermal sensitivity and visible wavelength diffraction limited spatial resolution make the NT200t the highest resolution thermal imager available for any price.

NT200t Technical Reference

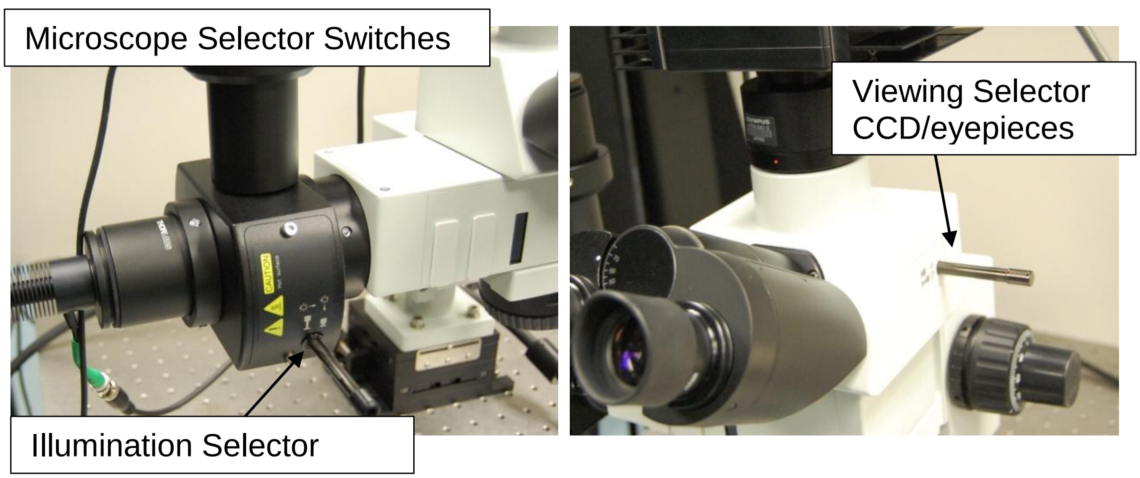
1. Quick Start Guide

1.1 Setup

- Make sure the NT200t has been installed on the optical table and checked by a qualified Microsanj representative.

- Ensure that the Transient Imaging Module, the SRS DS-345 function generator and the Microsanj 6040/202H pulse generator are turned on, the necessary connections made, and that the microscope LED and the device under test (DUT) are connected (refer to 2.4)

- Using the optical switches on the microscope select the white LED for illumination, and the eyepieces for viewing. Mount DUT under microscope and prepare to bias the sample. Using the eyepieces, make sure that the DUT is in focus and located on region of interest.



- Move the viewing, and illumination optical switches on the microscope to select the CCD, and the pulsed LED.

- Launch ThermoVIEW.exe from the program group on the computer

- Connect the SRS DS345 function output to the DUT.

Entering Values in ThermoVIEW:

Please use engineering notation when entering values into the ThermoVIEW software:

m= "Milli" = 10^{-3}
u= "Micro" = 10^{-6}
n= "Nano" = 10^{-9}

Displayed values also use the same convention

1.2 Thermal Image Acquisition

- Decide on the mode of imaging and set the "Image Type" selector in the project manager software.

Low Frequency Thermal Imaging:
This mode of thermal imaging uses unipolar sinusoidal excitation and frequency domain filtering to generate a thermal image: It is most appropriate for devices that have a time constant of 0.48Hz and higher. Please refer to Appendix A for the details of the thermal imaging techniques

Transient Thermal Imaging:
This mode of thermal imaging allows for thermal imaging at precise time points as the device heats. A series of frames can be acquired and a thermal movie of device heating can be created.

- Select the desired parameters for the transient or low frequency thermal image (refer to section 4.1 and 4.2 for detailed operation of the image acquisition software).

- Update the desired file path in the "Workspace Path" control. The workspace is where thermal images will be stored, and files accessed for processing the thermal images.

- Using the knob in the Project Manager set the % current value of the Microsanj 6040/202H LED pulse generator so that an image of the device under test (DUT) appears in the image window. In transient imaging mode, changing the parameters can change the output brightness in the imaging window.

- Once the image is in bright enough (indicated by ‘Good Illumination’ indicator in image display window), select the ‘Get Thermal Image’ button in the Project Manager window to begin acquiring thermal images.

- With the image acquisition software create data files to be used with the Thermal Image Analyzer software, under various biasing and delay conditions. (refer to section 4 for details). Use the ‘Output Voltage’ control as well as the ‘Current Delay’ (transient only) control to change the thermal imaging conditions.

1.3 Processing and Saving a Thermal Image

Please refer to section 5 for a detailed description of the image processing software features.

- Launch the ‘Thermal Image Analyzer’ from the Project Manager (‘Image Type’ selector must be set correctly).

- Load saved images by double clicking the file of interest.

- Use image masking if desired to correct for multiple thermoreflectance coefficients, and shadow features.

- Obtain quantitative thermal measurements by using the region of interest (ROI), and cross-section tools on the thermal image.

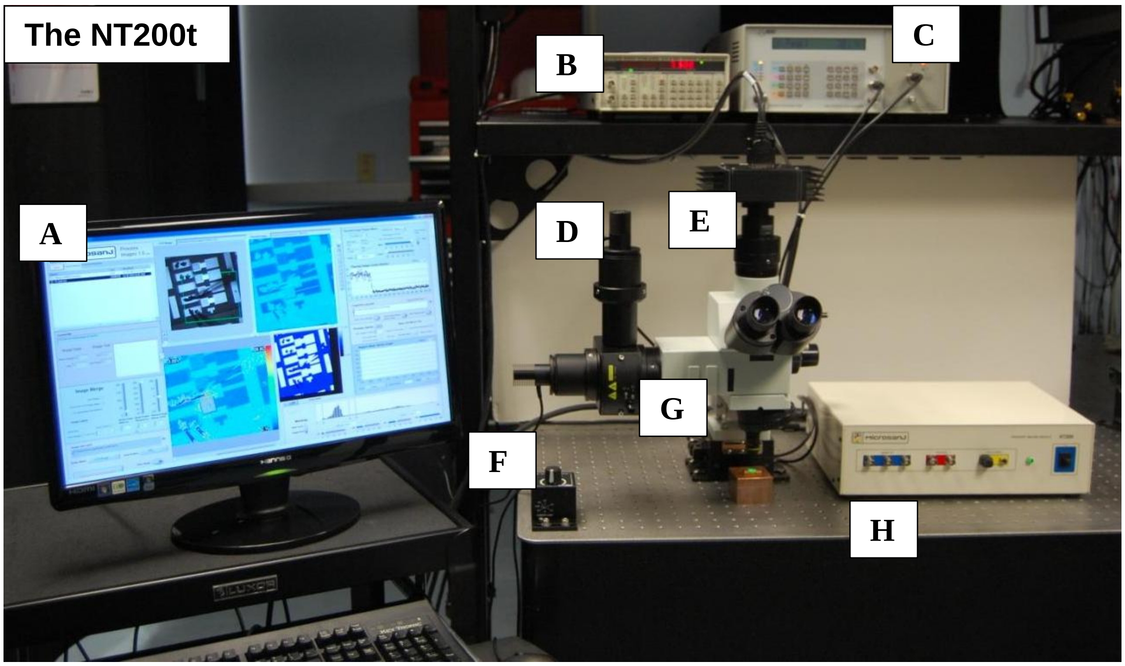
- If creating an image series or .AVI movie file, select the first image in the series, enter the number of files in the series, enter a base file name in the ‘Image Save’ path, and click the Process Series button.

- For a single image, either the CCD image, the thermal image, or the merged image can be saved in various image formats. Use the ‘acsii out’ option to use the images in Matlab or other processing software, as this preserves the highest resolution of the thermal data.

2. System Diagrams and Connections

2.1 Main Components

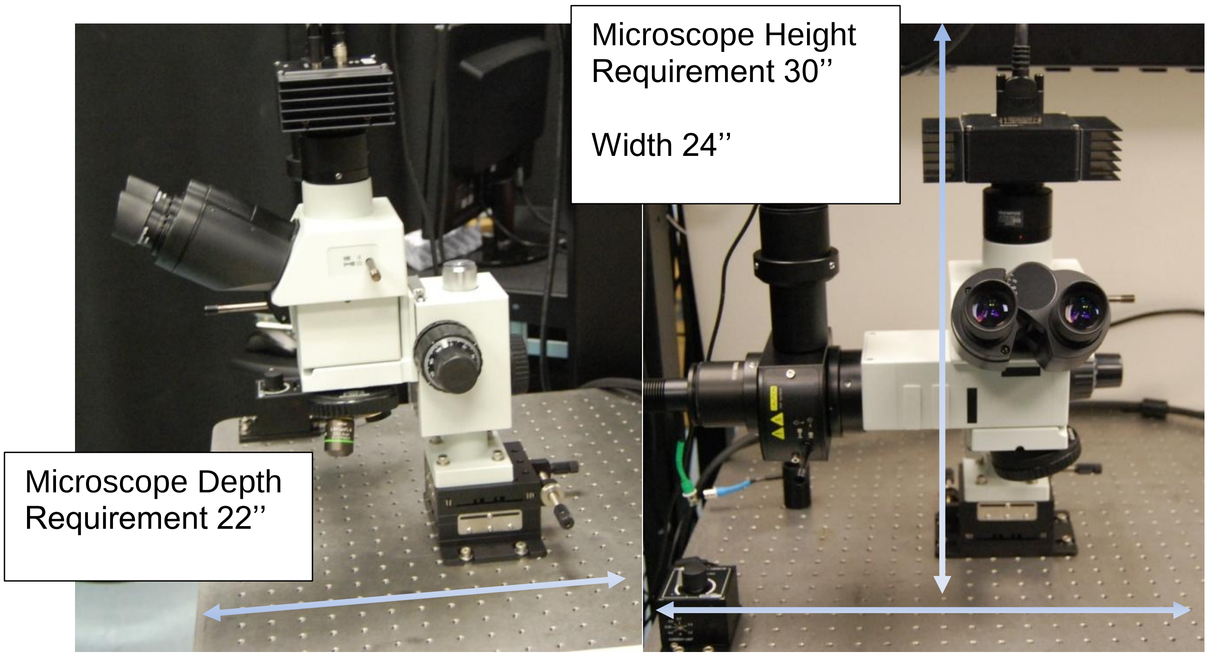
The Nantotherm 200 transient system (refer to Figure 2.1) consists of the following main elements:

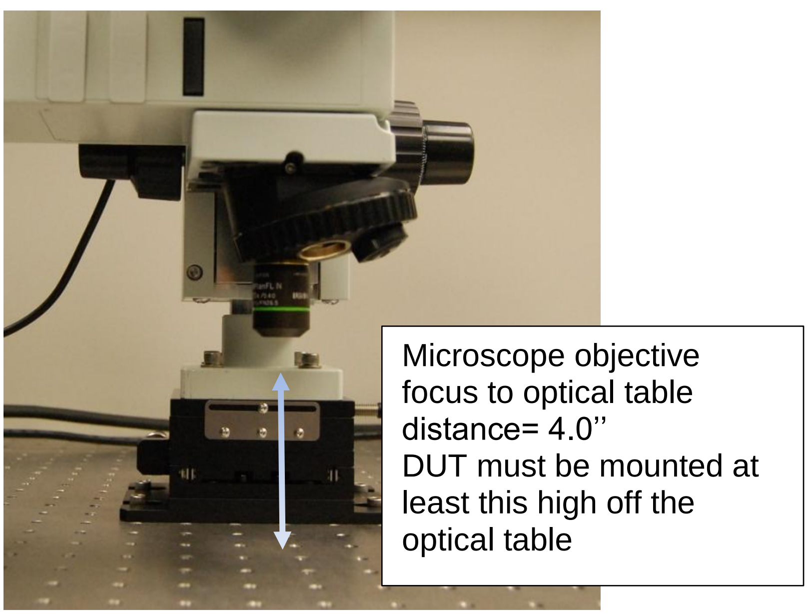


(A) Desktop Computer with ThermoVIEW software, National Instruments 1427 camera link PCI card, and 6602 counter/timer card installed.
(B) Stanford Research DS345 function generator
(C) Microsanj BNC 6040/202H pulse generator
(D) Green (530nm), Blue (470nm), and Near IR (780nm) Pulsed LEDs
(E) Dalsa 1M30 megapixel imaging CCD
(F) White Light illumination with controller
(G) Olympus BXFM optical microscope with multiple objective lenses
(H) Microsanj Transient Imaging Module (TIM)

2.2 Installation of the NT200 system

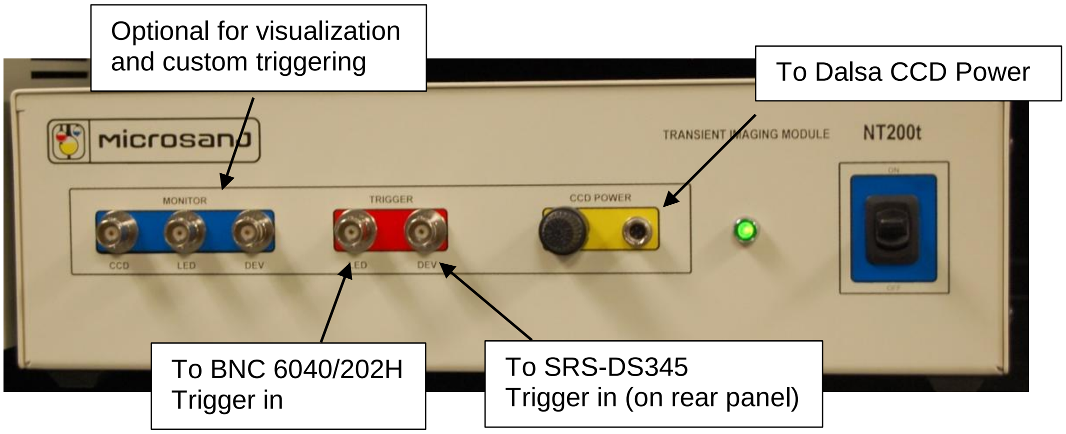
The Olympus Microscope is designed to mount to a standard optical table. The microscope is mounted on X-Y translation to allow for easy integration with a sample holder or microprobe station. Please observe the following dimensions for mounting clearance.



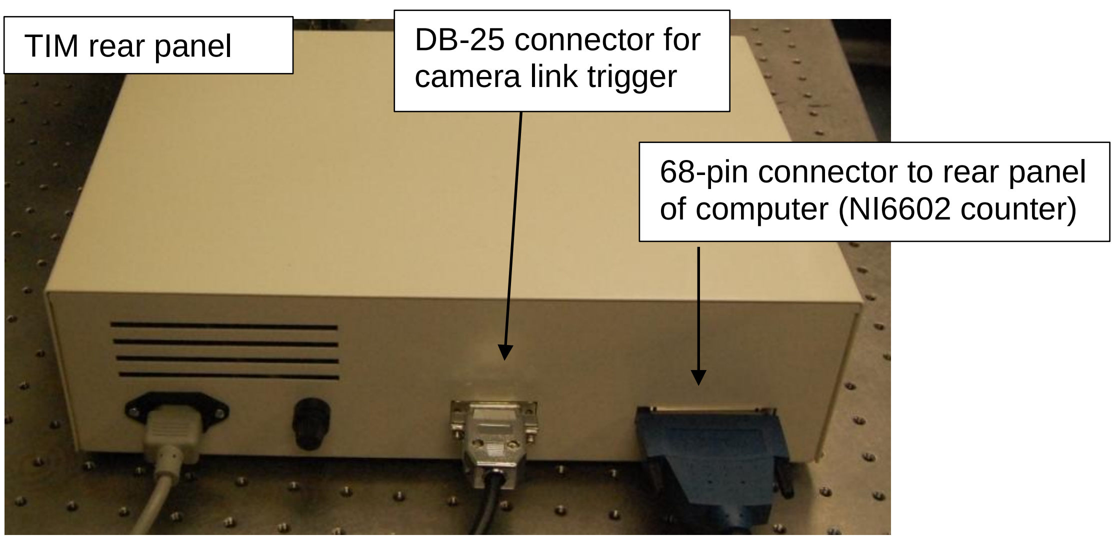


2.3 Transient Imaging Module

To create the necessary timing signals, the NT200t uses the Microsanj Transient Imaging Module.



The monitors CCD, LED, and DEV output the timing signals, and are buffered copies of the trigger signals for the CCD camera, the LED flash pulse, and the device excitation heating pulse. The monitors are provided to visualize the transient imaging timing points and can be used to trigger custom experiments. The outputs are TTL compatible and have output Impedance of 50 Ohms.



2.4 Connecting the cables

Please make sure the modules are powered down to make the following connections. Connections should be made and modules powered up prior to running the ThermoVIEW software.

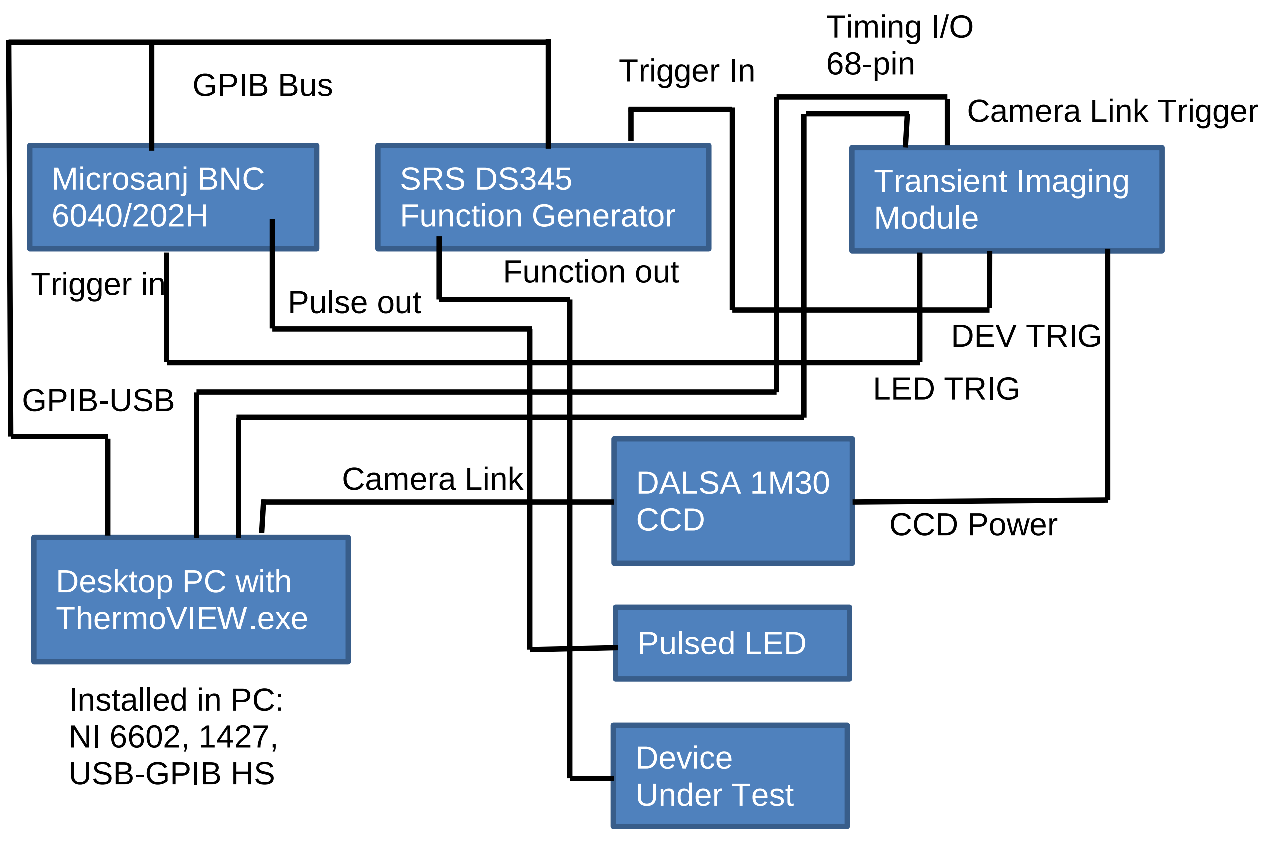
- Transient Imaging Module
  - Rear Panel:
    - 68-pin Cable to NI 6602 PCI card (Rear panel of computer)
    - DB-25 trigger cable to Camera link PCI card (Rear panel of computer)
  - Front Panel
    - CCD power connector to DALSA CCD power
    - LED ‘trig out’ to Microsanj BNC 6040 ‘trigger in’
    - DEV ‘trig out’ to SRS DS345 trigger in (on rear panel)

- Microsanj BNC 6040 Pulse Generator
  - Pulse out from the 202H module to pulsed LED unit via 50 Ohm BNC cable
  - ‘Trigger in’ to transient imaging module LED ‘trig out’

- SRS DS-345 Function Generator
  - Trigger in (Rear Panel) to Transient Imaging Module DEV trigger
  - Function out to Device under Test (Please verify function generator is outputting zero volts prior to connection)

- DALSA 1M30 CCD Camera
  - CCD camera link out to PCI camera link in (Rear Panel of Computer)
  - Power cable to Transient Imaging Module CCD power

- Desktop Personal Computer
  - National Instruments 1427 PCIe Camera Link Card Installed
    - Camera link connected to Dalsa CCD
    - Camera link trigger out to Transient Imaging Module
  - National Instruments PCI 6602 Counter Timer I/O
    - 68-pin Cable to Transient Imaging Module
  - USB-GPIB HS National Instruments
    - Connected to USB port on computer to GPIB bus on Microsanj Pulse Gen and SRS Function Gen.



NT200t System Connection Diagram

2.5 System Specifications

System Configuration	NT-200t
Thermal Imaging Method	Visible spectrum Thermoreflectance
Spatial Resolution (diffraction limited)	~400nm(diffraction) 230nm(sampling)
Thermal Resolution (typical)	0.2C
Active Thermal Pixels (horiz x vert)	1024 x 1024
CCD interface	Camera Link high speed, acquisition
Thermal Image Frame Update Rate	0.5 Hz
Software	ThermoVIEW software for control, analysis and automation
Timing Control	PCI based high speed signal generator with Transient Imaging Module (TIM)
Optical system	OLYMPUS BXFM series UIS optical system
Illuminator	Green (530nm), Blue(470nm), and Near IR Pulsed LED sources, and white light via optical switch
Microscope Objectives	Olympus PLAN infinity corrected 5x, 20x, 50x Long working distance option
Transient Option	Yes
Thermal Imaging Method	Short Pulse Visible spectrum Differential Thermoreflectance
Frame integration time(min)	100 +/- 12 nanoseconds
Max Movie Length	100 frames
Maximum Transient Period	30 milliseconds

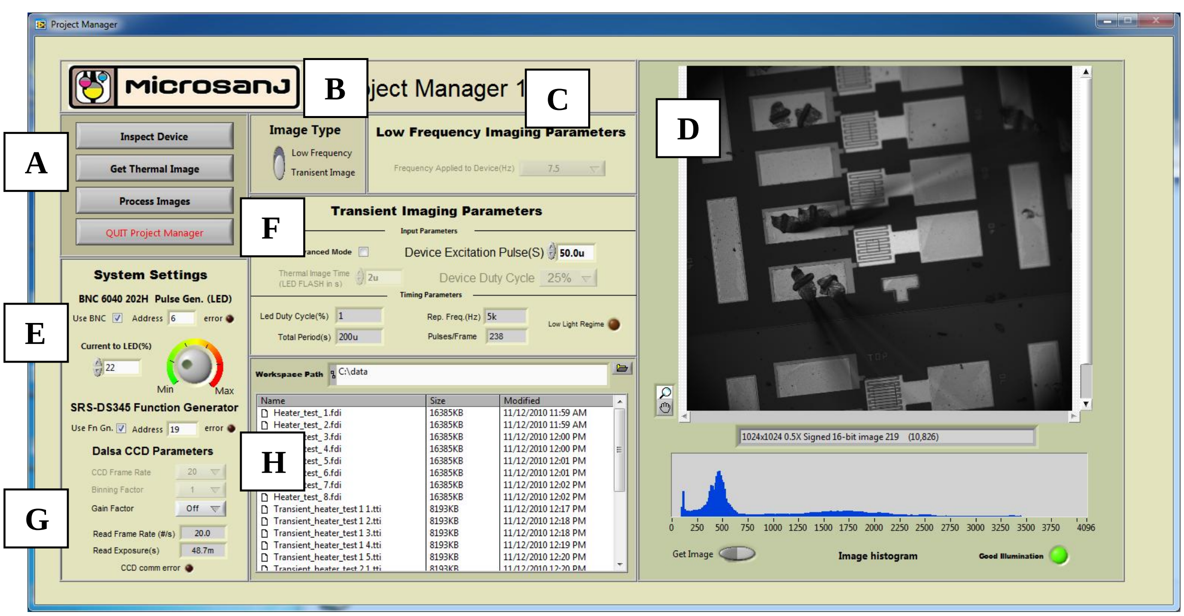
3. ThermoVIEW software application

The NT200t system is completely controlled by the ThermoVIEW application. The software should be run with the instruments powered, however if the desired session is for image processing only, Thermal image Analyzer will be available with the instruments off.

Thermoview has the following modules:

- Project Manager
  - Used for setting up the parameters of the thermoreflectance images and verifying the focus and illumination of the DUT
- Inspect Image
  - Used for setup of the DUT or device inspection
- Low Frequency Acquire Thermal Image
  - Create .fdi files which contain the raw data for the low frequency thermal images
- Transient Acquire Thermal Image
  - Create .tti files, which contain the data of the transient thermal image.
- Thermal Image Analyzer
  - Used to read the .fdi, and .tti files, and create output image files or .AVI move files

3.1 Project Manager



Main features of the Project Manager:

(A) Operation Select Buttons

These are the main selector buttons to: inspect the device, acquire a thermal image, or process a previously acquired thermal image with the Thermal Image Analyzer.

(B) Image type selector

Use the image selection to select the mode of operation. This selector applies to image acquisition as well as processing the thermal image.

(C) Frequency (Low Frequency Imaging Only)

This selector is only available in 'Low Frequency' imaging mode. The thermal image can acquired at the frequencies listed. The output to the DUT is a sinusoidal voltage at this frequency during thermal image acquisition. The available frequencies depend on the frame rate of the CCD, which can be either 20 or 30 fps.

> **Tip:**
>
> To zoom in and view features of the sample use the zoom tool (magnifying glass) and click on the region of interest. Use SHIFT-CLICK to zoom out.

(D) Image Display Window

When the 'Get Image' button is depressed, the image display should show an image of the DUT. Make sure there is enough illumination which is controlled by the white light or the pulsed LED (controlled by current % knob). Below the image display is a histogram of the CCD image, where on the left are the darkest points of the image, and the right indicates the brightest points in the image.

The 'Good illumination' indicator will light if there is enough illumination of the DUT to make a good thermal image. It is very important to have enough illumination to achieve good signal to noise (SNR) in the thermal image. If the indicator displays 'Too High' one or more of the pixels is saturated to the camera maximum. Only the pixels that are saturated are invalid, so if they are not near the region of interest, the data will still be valid.

(E) System Settings

System status shows the communication status with the three instruments controlled by the ThermoVIEW software. The Microsanj BNC 6040 and the SRS DS-345 use a GPIB interface to communicate via the National Instruments USB-GPIB-HS connected to the USB port of the computer.. The DALSA 1M30 camera uses a serial camera link interface via the National Instruments 1427 PCIe installed in the computer.

To troubleshoot GPIB connection issues:

- Make sure instruments are powered and the correct GPIB address is entered in the ThermoVIEW software. Default address for the BNC is 22 and for the SRS is19.
- Make sure the USB-GPIB is connected to a USB port and that the instruments are connected to the bus.
- Click the check box to attempt communication with the instruments.
- Make sure the instruments can be seen in the National Instruments Measurement and Automation (MAX) software using the ‘Scan for instruments’ option.
- If the user desires to use the ThermoVIEW software without the BNC or the SRS, uncheck the use instrument box, and the system should behave normally. Beware that in the Transient software, without using the GPIB instruments, the trigger in – pulse out delay will have to be considered, as the software is calibrated to the BNC and SRS instruments.

(F) Transient Imaging options (Transient Imaging Only)

There are several options associated with acquiring a “Transient Thermal Image’. First you must select weather the desired mode is ‘Basic’ or ‘Advanced’. Basic mode restricts the options settable, while using ‘Advanced Settings’ allows the user to input data in a much more flexible manner, but requires a little more knowledge of how the system functions.

Refer to appendix A for a more detailed review of how thermal images are acquired. The parameters are:

- Pulse width to device:
  - Controls the time width output by the function generator during thermal image acquisiton

- Thermal image time (LED Flash):
  - Allows the user to select the thermal image integration time, also the length of the illumination pulse created by the LED.

- Duty cycle to device:
    - Sets the duty cycle of the applied pulse to the DUT. Increasing the Duty cycle will increase the overall illumination, but also the total power delivered to the device which may lead to device overheating.

- Total Period:
    - The repetition period for the timing signals to the DUT and the LED. For each heating cycle to the device there is one LED pulse.

When using the advanced mode, the user can set the parameters, such that there can be very little light reflected off the sample. For example, as the thermal image time (LED flash) gets narrower, less light is generated. If the LED becomes less than 0.5% of the duty cycle the 'Low Light Regime' indicator will light, reminding the user the settings may allow for enough light to generate a high resolution thermal image.

(G) Dalsa CCD parameters:

Several imaging parameters are settable with the Dalsa CCD camera. The main function of these settings is to be sure that there is enough illumination on the DUT for thermal imaging. For low frequency and 'Basic' thermal imaging mode, the only settable parameter is the gain. In 'Advanced' mode several options are available to ensure that the illumination is high enough to get a thermal image.

To change the settings if the illumination is too low should be performed in the following order (Advanced transient mode only):

- Increase LED pulse current to 100%
- Increase the gain level
- Lower the frame rate
- As a last resort use the binning factor (x2 to x4)

If a very short illumination pulse is desired, some of the above settings may have to be used. Be aware that the overall SNR may decrease with low light conditions.

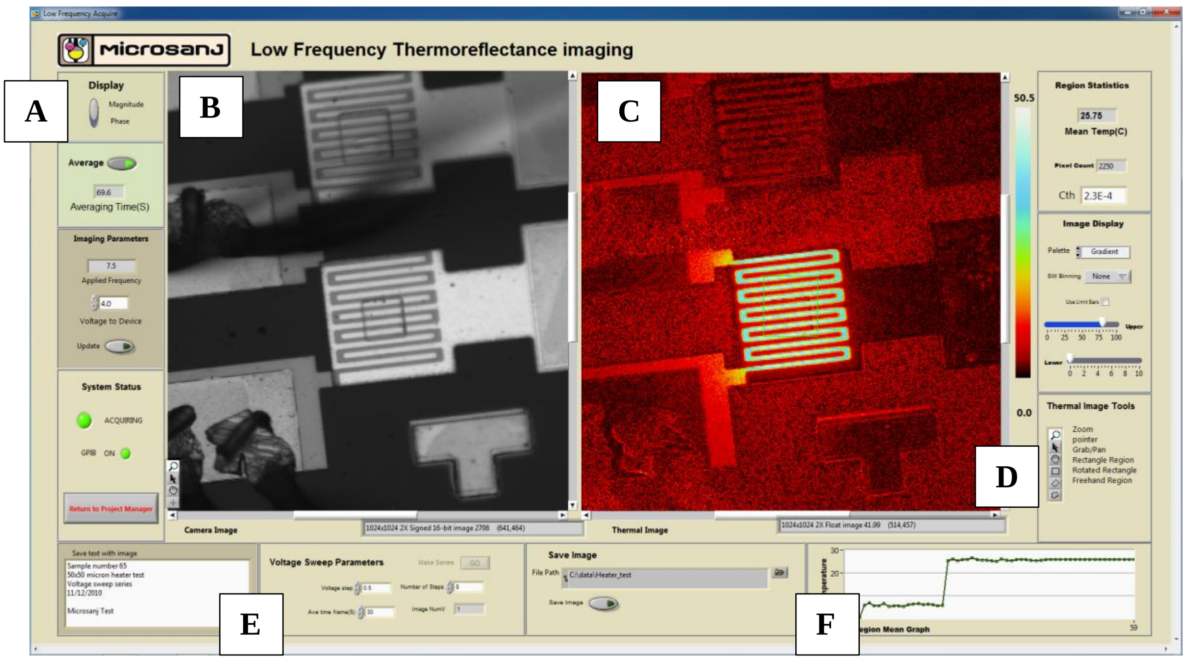
(H) Workspace Path selection

Use this file path entry to select the workspace for the imaging session, This is where the .tti (transient thermal image) or .fdi (frequency domain image) files will be stored by default.

4. ThermoVIEW: Get Thermal Images

Images are acquired in two modes as selected via the “Image Type” selector in the project manager. The appropriate program is launched when the user selects the ‘Get Thermal Image’ button. Please review Appendix A for a review of thermal imaging modes.

4.1 Low Frequency Thermal Imaging



(A) Thermal Imaging Parameters

Display:

This switch determines what is shown in the thermal image display window (C). The possible choices are Magnitude and Phase.

Averaging:

Use Averaging to increase the Signal to Noise (SNR) of the thermal image. Generally the improvement due to averaging increases rapidly but will plateau after several minutes. Averaging for 30 sec is recommended to achieve SNR of 0.5C in the thermal images (assuming Thermoreflectance Coefficient of 2.5 x 10^{-4}). The length of averaging time is displayed in the indicator.

Frequency:

This indicator shows the frequency of the offset sinusoid applied to the device, as was previously set in the Project Manager.

Output Voltage Control:

The output voltage to the DUT is controlled by the value here. Enter a voltage and press the update button to send the value to the DUT. The maximum output voltage (into 50 Ohms) is 5V. Into a high impedance load the output will be 10V.

> **Important:**
>
> The output impedance of the SRS DS-345 is 50 Ohms, and the control voltage is calibrated to a 50 Ohm load. When driving a high impedance load the voltage will be twice that of what is displayed numerically. Be sure to take this into account when testing devices. For best performance match the DUT's impedance to 50 Ohms.

Use GPIB indicator:

The status indicators indicate whether or not the GPIB is in use (Previously selected on the Project Manager). Low frequency thermal image acquisition is valid should one illuminate the DUT using a continuous wave (CW) source, rather than the pulsed LEDs with the BNC6040/202H. This allows coupling of specific wavelengths not available from the pulsed LEDs. In this case, the use GPIB should be de-selected and the indicator will display this.

It is recommended to always 'use GPIB' with the function generator as the low frequency thermal image requires an offset sinusoidal excitation, synchronized to the CCD. If higher current (or voltage) is required to excite the DUT then is provided with the function generator, the recommended solution would be to use the function output to drive the modulation input of a high current (or voltage) driver. For example one can connect to the ILX Lightwave model 3223 to extend the current range. Please remember that the output impedance of the DS345 is 50 Ohms and when driving a high impedance (like the '3232) the voltage will be twice that of what is displayed.

(B) CCD Image Display

This indicator shows the DUT during thermal imaging. Use the zoom tool (magnifying glass) to look at different regions close up. Use SHIFT-CLICK to zoom out. Also available is the pan tool (hand) which can be used to move to different parts of the image. Below the CCD image is the image information bar, which shows the image size in pixels, and also the location and value of the image (in grayscale) where the cursor is located.

(C) Thermal image display

The thermal image has the zoom tool, the pan tool, and a few different ROI tools used to obtain the value of the thermal image in different regions. The thermal image is calculated using the thermoreflectance coefficient to display the magnitude of the thermal image. When the display is set to 'Phase' the output is the phase image in radians, and the thermoreflectance coefficient is not considered.

The Thermoreflectance Coefficient:

To calculate the thermal image the software relies on the user input Thermoreflectance coefficient (Cth). This coefficient is material and wavelength dependent and can be experimentally obtained for a specific wavelength and material. Please see Appendix A (section 6.2) for more information about calibration and the thermoreflectance coefficient.

(D) Region of Interest tools

While the thermal image is being acquired, one can use the region of interest (ROI) tools to obtain an average temperature. To calculate the temperature of the DUT at a specific voltage the software utilizes the Thermoreflectance coefficient (Cth) for that specific region.

(E) Make voltage series

It is possible to perform a voltage sweep for different voltages and create a series of thermal images as a function voltage.

To create a voltage series:

- Enter a base file name in the thermal image save control.
- Set the parameters in the Make Voltage Series box. The parameters are voltage step, averaging time, and total number of images.
- Enter the starting voltage in the Output Voltage control and click 'update'. The voltage sweep starts (first image in the series) at the current value of the output voltage.
- Depress the "Make Series" control in the software. The averaging process should start and the images created.

- The images will be number 1..N as appended to the data file.

(F) Region of interest history

The strip chart show the history of the ROI in the thermal image. To clear the value of the chart RIGHT-CLICK, and select clear chart.

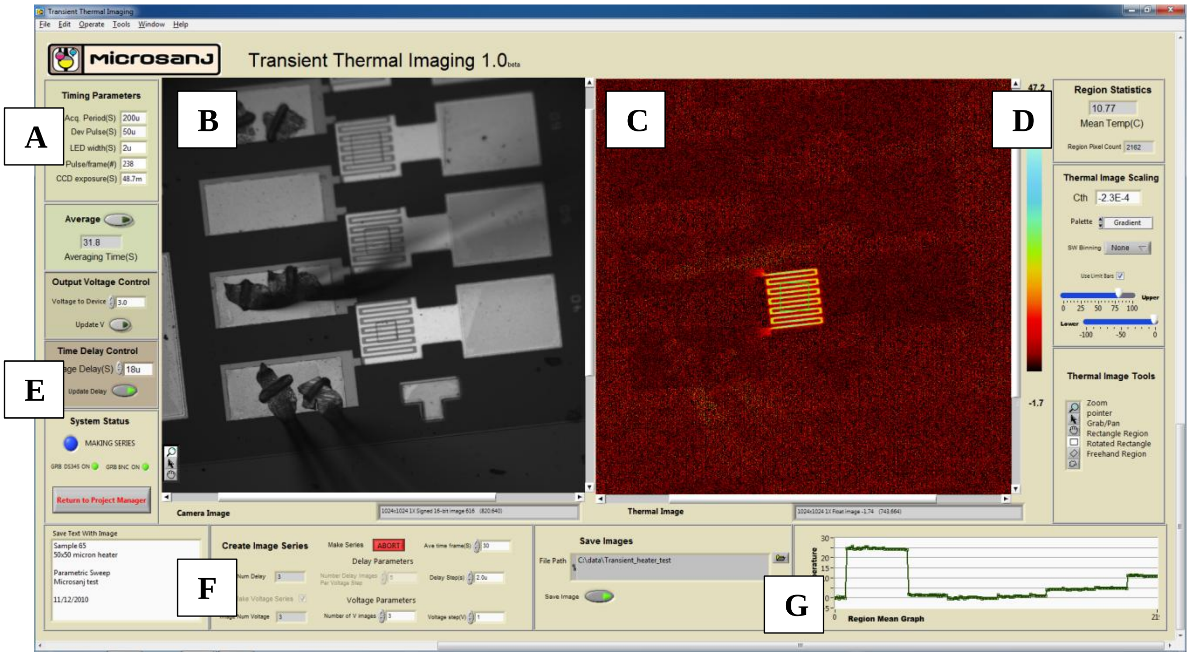
Low Frequency Imaging CW Illumination:

It is possible to obtain low frequency thermal images without using the Microsanj BNC 6040/202H LED pulse generator. The thermal image will still be valid if the illumination is CW (non-pulsed). This allows the user to illuminate with light that is not limited to the pulsed LEDs provided. Certain materials may require specific wavelengths of illumination to enhance the thermoreflectance coefficient. For example it is possible to use the white light illumination and bandpass filters, to choose a specific wavelength.

Please disable the pulse generator (uncheck use BNC 6040/202H in project manager) when using CW illumination so as to not cause unnecessary wear on the BNC and pulsed LED.

4.2 Transient Thermal Imaging

Transient imaging is used to generate thermal image ‘snapshots’ at specific timing points in the DUT’s heating cycle, or thermal image ‘movies’ which are a series of images. This imaging mode is most applicable to devices with thermal time constants from 1 microsecond, to 10 milliseconds.



(A) Thermal Imaging Parameters

The indicators show various parameters that were setup in the Project Manager.

Averaging control and Averaging Time indicator:

Use Averaging to increase the Signal to Noise (SNR) of the thermal image. Generally the improvement due to averaging increases rapidly but will plateau after several minutes. Averaging for 30 sec is recommended to achieve SNR specifications.

Output Voltage control:

This selector controls the output voltage to the DUT via the SRS function generator. The width of the pulse is selected in the Project Manager and indicated in (A). For optimum impedance matching use a 50ohm cable and match the device impedance to 50 Ohms if possible.

Important:

The output impedance of the SRS DS-345 is 50 Ohms, and when driving a high impedance load the voltage will be twice that of what is displayed. For best performance match the DUT's impedance to 50 Ohms.

(B) CCD Image Display;

Shows an image of the device being thermally imaged.

(C) Thermal Image Display

The currently acquired thermal image is shown in the display. The thermal image is calculated using the thermoreflectance coefficient entered in the thermoreflectance input control on the panel. Additional options are to change the displayed image color palate, and

(D) Region Statistics

Several different region of interest(ROI) tools can be used to find the average temperature of different areas in the thermal image. They are:

- Rectangle tool
- Rotated Rectangle
- Annulus Tool
- Free Hand region
- Circle region

Limit Bars:

The limit bars can be used to zoom in the temperature scale of the thermal image. When the limit bars are active the data that is above or below the limits is set to the value of the limits. Be aware that the ROI mean tool may not be exactly correct if the limit bars are used.

(E) Delay Control:

Use the delay control to acquire the thermal image during different times in the DUT thermal cycle. The value of the delay corresponds to the falling edge of the LED illumination pulse which is also the end of the thermal image integration time. For example if the DUT pulse width is 50us and the LED pulse is 2us, with the delay set at 50us, the thermal image will be an average of the thermal signal from 48us to 50us. To generate a thermal image series, use the make series controls as described in (B).

Use GPIB Indicators:

The indicators show whether or not the GPIB was selected to use the Microsanj BNC6040/202H, and the SRS DS-345. It is possible, but not advised, to use the transient thermal imaging without pulsing the LED with the BNC 6040/202H. An equivalent pulse generator must be used and trigger via the TTL 'LED TRIG' output of the Transient Imaging Module.

(F) Make Series

These settings are for generating a thermal image series, either at different time delays, or at different voltages. Either a voltage or delay series can be turned into a .avi file in the image processing application. It is also possible to make a sweep of voltage and delay together. To set up the series observe the following parameters:

- Averaging time:
  - How long each image in the series will be averaged

- Delay Step:
  - Between each image in the series the image delay is increased by this amount

- Num image per delay step:
  - This is the total amount of images to be taken for the delay series. Be aware that if a voltage series is desired, the system will acquire this many images for each voltage step.

It is important to remember that the delay step should not be set to less time than the thermal image time, because this will create overlap in the data points. The result will be a smoothing of the data.

- Make Voltage series checkbox:
  - Selecting the make voltage series option will generate a voltage sweep for the thermal images.

The filenames will be of the format: user entered base filename, appended with the voltage number, and then the delay number. Both a voltage and Delay sweep can occur together. By setting up for a delay sweep then checking the make voltage series box, the delay series will be recorded for every voltage step.

Voltage Series Example:

Suppose a thermal image series is desired for a DUT from 0 to 4 V. Appropriate settings would be:

Number of images =8
Voltage Step = 0.5V
Averaging Time = 30 sec
Num Delay images per voltage = 1

Then, make sure the Output Voltage is set to 0.5 Volts, a file name is entered, and click ‘Make Series’. The result should be 8 images created after about 4 minutes.

Delay Series Example:

Suppose a thermal image series is desired to investigate the thermal transient turn on time for a DUT at 4 Volts biasing. We assume that the timing parameters have already been setup in the Project Manager. Device excitation = 50us, thermal image time = 2us

Delay Step = 2us
Averaging Time = 30 sec
Num Delay images per voltage = 30
“Make Voltage series” is unchecked

Then, make sure the current delay is set to 0 seconds (series starts where the current delay value is set). Input a valid filename. Clicking on “Make Series” will initiate the series creation.

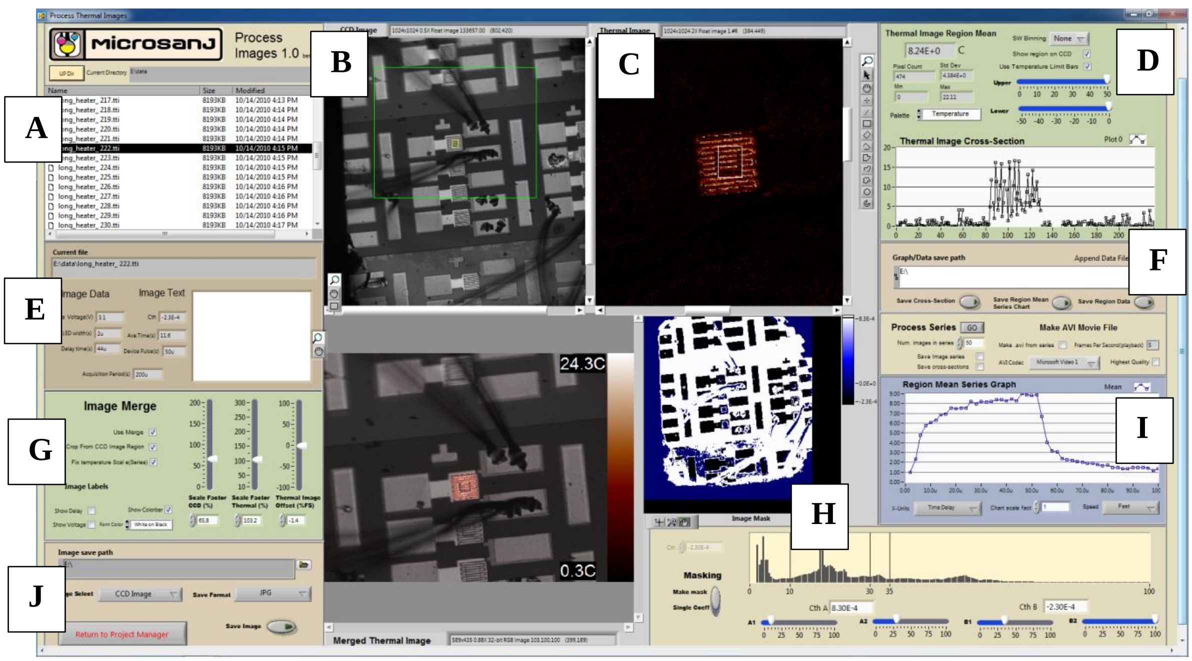
(G) Chart recorder of region mean

The chart recorder plots the value of the ROI mean for each thermal image. To clear the chart RIGHT-CLICK and select clear chart.

5. ThermoVIEW: Thermal Image Analyzer

Using the Thermal Image Analyzer you should be able to:

- View previously acquired thermal images
- Correct for 2 thermoreflectance coefficients
- Find region mean values, and create cross-section plots.
- Output the images in various image formats
- Create .AVI movie from image series



(A) Load a thermal image

There are two different types of files that are created in the ThermoVIEW software, depending on if the data is a Low Frequency, or Transient thermal image. Low frequency data files use a .fdi extension, while the Transient data files use a .tti file extension. This is the raw data from which the thermal images, cross-sections, and region data, are created. Depending on which type of session (from the image type selector) is selected the image processing will only show those files and options.

Load a thermal image by double clicking on the file that contains the image of interest. The CCD image and the thermal image should load and appear in the image display windows.

(B) CCD image Display

The image of the device should be shown in the CCD image display. The image tools available to the user are the grab tool (hand) the zoom tool (magnifying glass) and the region select tool (square). The hand will move the image around in the image display window. The zoom tool can be used to view close up regions of the image (SHIFT-CLICK to zoom out). The region select rectangle tool is used with the merged image (see G) to crop the thermal image in the region of interest.

(C) Thermal image Display

The thermal image is calculated differently depending on if the acquisition was a Transient image, or Low Frequency image. Refer to appendix A for more information on how the thermal image is calculated. The tools available to manipulate the thermal image, are the pan tool (hand) the zoom tool (magnifying glass) cross-section tool (line) and several region select tools. The region select tools are for using a predefined shape, or a freehand region to determine the mean temperature in a certain region. The thermal image contains the temperature information, and is calculated using the masked, or single value thermoreflectance coefficients (see H)

(D) Region of Interest statistics

Use the ROI selection to obtain a mean value of the temperature in the region selected. Several different ROI geometries can be used.

Cross-section graph:

One can look at various cross-sections of the thermal image by selecting the line tool and drawing the line on the thermal image. The resulting data is shown in the cross-section graph. If using masking, some of the data points might not appear on the graph, because they are masked out because they were determined to be invalid. RIGHT-CLICK on the plot legend to change the plot style.

Limit bars:

When a thermal image is loaded the image is auto-scaled to the highest and lowest data point in the image. This means that a few outlying data points can obscure the thermal image. The limit bars coerce the data to the limits selected. Use the mouse to select and change the limits of the bars.

Show Region on CCD:

Sometimes it can be a challenge to relate where the region in the thermal image is relative to the structure in the DUT, as shown in the CCD image. When a RIO or cross-section is selected in the thermal image, and the 'Show Region on CCD image' is selected, the region is shown on the CCD image.

Color Palate selection:

Several color palates are available for display of the thermal image. The selection of the color palate also shows up in the merged image. When the thermal image is save it will save with this selected palate.

Software binning:

Under certain conditions where the thermal image is faint, due to small temperature changes or a poor thermoreflectance coefficient, software binning may help. Binning is spatial averaging by adding the neighboring pixels and lowering the overall spatial resolution. Binning also can improve the signal to noise of a cross-section plot. Binning choices are x2 or x4.

(E) Saved Image information

Several experimental parameters are saved with the thermal image and are displayed here. The parameters are different depending on if the process image session is a low frequency or transient image. Also use this save path and name when creating an AVI output.

(F) Save path for ROI data and cross-sections

Use this path to enter the saved data for the cross-section, ROI data, and also the region mean graph (created with auto-process). The output file is ASCII text to be used with your favorite plotter.

(G) Merged image

The merged thermal image is use for display and saving only as the temperature values are contained in the thermal image. The merged image is used to generate a thermal image which conveys information about the temperature distribution. The merged image has been converted to a single precision numeric value to a RGB image, allowing for compatibility with image output formats.

The merge tool uses three sliders to create the merged image. The first slider shows the percent of CCD image that is overlaid onto the thermal image. This can be useful to identify the exact location of hotspots in a thermal image. Next are the gain and offset sliders, which both apply to the thermal image. If the sliders are set to %100 and 0% the gain and offset are unchanged relative to the thermal image display. It is possible to use these sliders to emphasize different features of the thermal image.

Crop from CCD image checkbox:

Use this feature to crop out the part of the thermal image that may be far from the region of interest. Select the rectangle tool on the CCD image and draw a box around the desired region to crop. This tool can be especially useful when creating AVI movie files, as the size the move files can be reduced by elimination the part of the image that does not have thermal information.

Fix temperature scale checkbox:

This check box is primarily used when creating an image series movie, or output images. With this button depressed the scale that has been previously set will not change when a new file is loaded. The suggested way to use this tool when processing an image series is to find the hottest image in the series, and set the scale to the desired level, then check the fix scale checkbox. Now go back to the first image in the series and run the process series tool. The result will be that rather than auto-scaling each image, the temperature scale will be fixed throughout the image movie.

Show voltage/delay/colorbar checkboxes:

These tools are available to display on the image the conditions under the acquisition and also the color showing the temperature mapping of color to the thermal image.

(H) Image Masking

Masking is an important tool which allows for setting of multiple thermoreflectance coefficients and also eliminates shadows, and other regions that do not have valid thermal data. Proper masking can take a little practice, to get it just right. If masking is not desired, the user can select ‘single coefficient’ and one coefficient is applied to the entire thermal image.

The mask display shows the current mask, and underneath is an image histogram of the CCD image which is used to create the mask. The sliders A1, A2 and B1, B2, represent the limits for the coefficient applied to the two surfaces. The regions outside the limit bars are considered NaN (not a number) and are omitted from the cross-sections, and region of interest calculations.

To make a mask:

- Masking for two coefficients requires knowledge of multiple thermoreflectance coefficients
- Select ‘Make Mask’ from the selector
- Slide the A1 slider from 0 (darkest points) to the right until the shadows are shown in the mask display
- Slide the A2 slider such that the data points included in the A1 to A2 band represent the dark surface that should receive the first thermoreflectance coefficient.
- Slide B1 and B2 so that they will apply the bright thermoreflectance coefficient to the bright material. Often B2 is left at %100
- The resulting mask in the display window should show the created mask, and the scale reflects the coefficients applied to the thermal image

The mask display has a few tools that can be used by clicking on the tool select just below the graph display. The region zoom tool is useful for ensuring the correct masking in the region of interest. Auto-scaling of the mask display can be set by RIGHT-CLICK on the display window.

(I) Process Image Series

If an image series (Voltage or Delay) has been previously created, several tools are available to obtain data from the images. When the ‘Go’ button is pressed, each image in the series is sequentially loaded and a movie is made, or a graph is created. Additionally a series of cross-sections can be saved at the touch of a button. For the data plots, use the data save path (F), for saving a series of images or a AVI movie use the image save path control (J).

The region mean series graph is use to plot the selected region mean (see D) for each image in the series. The x-axis can automatically plot either voltage or delay on the axis, by changing the selector. Another option is slow, medium, or fast, speed used during the auto-process feature. In processing image series, the series will be processed faster if the image merge and single coefficient masking options are not used.

(J) Image output Options

The CCD image, thermal image, and merged image, can be saved in a variety of output formats. When saving the image, it is converted to an RGB image (for compatibility with the image data types), and thus it is important to remember that the images are for visualization only because they do not preserve the temperature data. If one desires to use the images with another program for separate calculations, (ie. Matlab), the images should be output in 'ASCII' format, to be loaded in the same way and thus the numeric thermal information is preserved. The CCD data is output in unit-less gray levels, which is also dependent on the averaging time.

6. Appendix A

6.1 Thermoreflectance imaging fundamentals

Thermoreflectance thermal imaging relies on a linear change of a material's reflection coefficient with temperature. This effect was first noted in the 1960's but not until recently have the techniques for thermoreflectance thermal imaging come to fruition.

Many scientific papers on the subject have been written and the reader is encouraged to refer to the following publications:

J. Christofferson, K. Maize, Y. Ezzahri, J. Shabani, X. Wang, and A. Shakouri, "Microscale and Nanoscale Thermal Characterization Techniques", in J. Electronic Packaging, Dec 2008, Vol. 130, Issue 4, 041101

Y. Ezzahri, J. Christofferson, G. Zeng and A. Shakouri, "Short time transient thermal behavior of solid-state microrefrigerators", J. Appl. Phys, 106, 114503, (2009).

B. Vermeersch, J. Christofferson, K. Maize, A. Shakouri, G. De Mey, "Time and Frequency Domain CCD-Based Thermoreflectance Techniques for High-Resolution Transient Thermal Imaging", Proceedings of IEEE 26th SEMI-THERM, Feb 23-25, Santa Clara CA, pp. 228-234, 2010.

"Non-Contact Transient Temperature Mapping Of Active Electronic Devices Using The Thermoreflectance Method," Mihai G. Burzo, Pavel L. Komarov, and Peter E. Raad, I*EEE Transactions on Components and Packaging Technologies*, Vol. 28(4), pp. 637- 643, 2005.

"Performance Analysis of the Transient Thermo-Reflectance Method for Thermal Conductivity of Single Layer Materials," Pavel L. KOMAROV, and Peter E. RAAD, *International Journal of Heat and Mass Transfer*, Vol. 47, pp. 3233-3244, 2004.

M. Farzaneh, K. Maize, D Luers, J.A. Summers, P.M. Mayer, P.E. Raad, K.P. Pipe, A. Shakouri, R.J. Ram, and Janice A. Hudgings, "CCD-based thermoreflectance microscopy: principles and applications," *Journal of Physics D: Applied Physics*, vol. 42, p.143001, 2009.

M. Farzaneh, Joe Summers, R.J. Ram, and J.A. Hudgings, "Thermal and optical characterization of photonic integrated circuits by thermoreflectance microscopy," *Journal of Quantum Electronics*, vol. 46 (1), p.3-10, 2010.

Because of the small changes in the reflection (imperceptible to the human eye) high resolution, low noise equipment must be used, and sophisticated averaging schemes are used. The NT200t provides two modes of averaging and are described in the following section.

Low Frequency Imaging:

Low frequency imaging uses a frequency domain filtering technique to resolve the minute change in reflection for thermal imaging. The major advantage of this technique is twofold: It can be done without pulsed illumination, and lower frequency thermal images (down to 0.48Hz) then in “Transisent” mode are possible.

Low Frequency Imaging Illumination:

It is possible to obtain low frequency thermal images without using the BNC 6040/202H LED pulse generator. The thermal image will still be valid if the illumination is CW (non-pulsed). This allows the user to illuminate with light that is not limited to the wavelengths of the pulsed LEDs provided. Certain materials may require specific wavelengths of illumination to enhance the thermoreflectance coefficient. For example it is possible to use the white light illumination and a bandpass filter, to choose a specific wavelength.

Please disable the pulse generator (uncheck use BNC 6040/202H in project manager) when using CW illumination so as to not cause unnecessary wear on the BNC and pulsed LED.

Transient Thermoreflectance Imaging:

In order to see the heat evolving in the DUT, it is possible to obtain thermal images at particular ‘snapshots’ in the heating/cooling cycle of an active device. Through precise timing of when the illumination flash occurs, and when the device is excited, the high resolution thermal image is calculated. This mode of averaging has a slightly lower noise floor (0.2C vs. 0.5C) then the low Frequency and is therefore preferred when possible.

Acquiring a transient thermal image series allows one to visualize the change in the device during the active heating cycle. The tools in the thermal imaging analyzer can display the temperature of a given point in the image at different times.

6.2 Calibration

In order to have accurate thermal images it becomes necessary to have knowledge of the Thermoreflectance coefficient of the material that that is in the thermal image. Please refer to the tabulated values for thermoreflectance coefficients of common materials:

Material	Green LED (530nm)	Blue LED (470nm)	Near IR (780nm)
Aluminum	<1 x 10^{-6}	<1 X 10^{-6}	1.2 x 10^{-4}
Gold	-2.5 x 10^{-4}	1.9 x 10^{-4}	
Silicon	2.0 x 10^{-4}	3.4 x 10^{-4}	

When the region of interest is covered with Aluminum, it is advisable to use the provided 780nm LED. The thermoreflectance coefficient at the wavelengths of 530nm (green), and 470nm (blue), is too small to provide usable thermal images.

Often a material may have a thin layer of material that is nearly invisible to the CCD camera (or the eye) such as an oxide, or nitride layer. This may have an effect on the value of the thermoreflectance coefficient. In many situations it may be better to perform a calibration test, rather than relying on book values. Several articles have been written on how to determine the thermoreflectance coefficient:

"Thermoreflectance temperature imaging of integrated circuits: calibration technique and quantitative comparison with integrated sensors and simulations"
G Tessier et al 2006 J. Phys. D: Appl. Phys. 39 4159

"Pixel-by-pixel calibration of a CCD camera based thermoreflectance thermography system with nanometer resolution", Burzo, M.G. Komarov, P.L. Raad, P.E. Thermal Investigations of ICs and Systems, 2009. THERMINIC 2009

The typical method to find the thermoreflectance coefficient is to externally heat the sample to a uniform temperature (externally measured by a thermocouple) then measure the change in reflection, for the sample of interest. The ratio of the normalized reflection change to the temperature change gives the value of the coefficient.

7. Appendix B

7.1 Microsanj BNC Pulse Generator Manual

8. Appendix C

8.1 Dalsa 1M30 CCD Camera

8.2 Olympus BXFM Series Microscope