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Development of Infrared Thermal Mapping Technique for Electronic Devices

by

Sanjay Ailani

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Abstract

Development of Infrared Thermal Mapping Technique for Electronic Devices

Sanjay Ailani

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The goal of this research project is to develop an experimental setup that is capable of demonstrating thermal behavior of the electronic device. The project focuses on thermal mapping at device, integrated circuit and printed circuit board (PCB) level.

A unique technique to perform thermal mapping on integrated circuits and printed circuit board based on Infrared Thermography is proposed in this research project. The developed experimental setup is capable of performing steady state and transient analysis at device and PCB level. The proposed test setup is applied to perform thermal mapping on 68HC11 microcontroller board to predict accurate temperature distribution on the real time operating printed circuit board. The accuracy and validation of the experimental setup are the two major challenges faced in this work. Apart from this, to know the exact transistor junction temperature, it is necessary to develop methodology that prevents heat spreading, allows proper cooling and the one that provides stable cooling thermal coefficient.

The performance of infrared thermography has been validated against thermocouple results. The experimental results are compared with the ones obtained by digital thermometer. In order to achieve stability and certainty in the results, insulated environment is preferred. Thermocouple results can be taken as reference since it is in physical contact with the die or the package. Cooling of the electronic device is also performed in this work. Oil based heatsink has been implemented using mineral Aldrich oil which is specially designed for IR spectroscopy. Several different combinations of layers of coating of Boron Nitride spray and black spray paint are deployed with different emissivity settings. The effect of the number of color layer coatings and emissivity values have been investigated. Various challenges pertaining to heat spreading, heat dependent cooling coefficients and spatial resolution have been resolved. The performance of the test setup has been evaluated for both steady state and transient analysis. In addition, thermocouple results have been taken as reference.

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Chapter 1

Introduction

Shrinking device sizes and higher integration densities give rise to numbers of new challenges in designing the next generation of integrated electronic components. The reasons are due to ongoing push of technology towards higher speed and device density and/or higher power and increased complexity. The resulting effects of the size reduction and increased power lead to higher heat generation per unit area. Without accurate prediction of the temperature profile, it is impossible to determine properly the electrical characteristics of devices and therefore these devices may be at risk of overheating thus causing early device failure. When a device operates at high power dissipation, self-heating and thermal coupling are the main issues in its performance and reliability [1-2]. Device temperature enhancement affects its electrical properties such as operating frequency, power dissipation, ionization rate, and carrier mobility and saturation velocity [3].

The ability to improve the chip and system performance for future products will directly depend on the development of an understanding of power distribution and thermal distributions. Towards this end, a key technical challenge involves the optimization of circuit designs and software tools to avoid excessive power consumption and non uniformities in the heat load [4].

While substantial progress has been made in modeling of temperature and power distributions of electronic devices [5,6], detailed and quantitative experimental measurements for verifying these models are not available. In order to address this shortcoming, a need exists for “real-time” temperature and power mapping of fully operating electronic device chips.

Thermal Mapping relates to temperature measurements and more particularly to systems for methods of determining and indicating the temperature characteristics of an object so as to derive a high resolution, two-dimensional graphic representation of surface temperature of an object [7]. It is important for designers and manufacturers to have accurate knowledge of a monolithic integrated circuit. The presence of the “hot spots” on

the surface of an IC may create reliability and performance issues. If the locations of hot spots are known with high resolution, designers may be able to modify IC layout to optimize dissipation or mitigate the problem via other techniques known to those in art. The feasibility of the different thermal testing procedures is inherently linked to the existence and performance of temperature monitoring techniques.

A commonly used method for thermal mapping of ICs is infrared thermography. Infrared thermography transforms the thermal energy, emitted by objects in the infrared band of the electromagnetic spectrum, into a visible image. Results may be regarded from two points of view, either as validating infrared thermography as a full measurement instrument or as a presentation of infrared thermography as a novel technique, which is able to deal with several requirements that are difficult to perform with other techniques. Infrared thermography (IRT) is a non-contact, non-intrusive technique, which enables us to see thermal energy [8]. In fact, a radiometer transforms the energy radiated from objects in the infrared band of the electromagnetic spectrum into an electronic video signal and ultimately into a visible image; each energy level may be represented by a color, or a grey level. The energy emitted by a body is mainly a function of its surface temperature and so infrared thermography may be considered as a two-dimensional technique of temperature measurement.

1.1 Thesis Objective

The goal of this project is to develop the capability using advanced experimental methods to investigate the *accurate thermal mapping technique for real time operating integrated circuits*. The objective of thermal mapping technique is to develop the method that can find accurate temperature distribution over a PCB or IC. 'Hot spot' can be determined in the device, which provides valuable information regarding which component of device gets heated up at maximum temperature. A hot spot reduces reliability, shorten the lifetime, or even immediately burns out the chip [9]. The temperature of the hot spot varies from one device to the other. For example, the temperature of hot spot on the system on which we have performed experiments is 35°C. This approach will give the most realistic approach because testing is done in the

operating condition and enable designers to find an appropriate arrangement of circuit blocks with a nearly uniform heat distribution.

Using infrared thermography, thermal mapping is done with great level of accuracy. The advanced infrared camera used in this research project is FLIR SC4000, which is located at Electro-thermal Laboratory. The overall experimental setup consists of advanced FLIR SC4000 infrared system, continuous heat removal setup and the data acquisition system at 50 mega pixels with image rate of 125 fps. The IR system results have been validated against thermocouple results, and percentage errors are compared to the ones obtained in the literature. Emissivity and cooling of electronic devices have been addressed in this work. Different setups have been developed to achieve uniform emissivity and an efficient cooling of the electronic device.

The system used for the experiment was IPB V1.0 board, which is a 68HC11 microcontroller board. Even though the method was implemented on microcontroller board, it can be used on any high power density circuits such as motherboards, PCIExpress Cards, in short for all the VLSI circuits. Emissions from the backside of an integrated circuit may be measured to determine variety of defects, such as, impact ionization, shorts, hot carrier effects, forward and reverse bias P-N junctions, transistors in saturation and gate oxide breakdown. The modifications that can be made for testing of different systems are also suggested. The post processing of the images and temperature results is also performed to get better idea of the hot spots [10, 11].

1.2 Thesis Outline

The first four chapters are designed to present the fundamental building blocks in thermal mapping techniques. Chapter 2 discusses a general introduction to heat transfer that takes place in any electronic device or system. The available thermal mapping methodologies in literatures are elaborated in chapter 3. In chapter 4, infrared thermography is introduced. In addition, different issues related to different setups are also discussed in detail. The proposed modifications to be performed on the setup for different electronic systems are also discussed. Chapter 5 focuses on system on which the

given methodology will be implemented. It also includes details and specifications of Infrared Camera used during experiment efforts.

The proposed technique for thermal mapping is discussed in Chapter 6. It also presents the implemented experimental setup. The procedure of performing experiments has been discussed.

The test results obtained from thermal mapping of 68HC11 microcontroller board for steady state and transient analysis are discussed in Chapter 7. These results are compared to the available results to validate the accuracy of the new setup. Parametric study of emissivity and other important parameters affecting the temperature contour are also discussed.

Finally, conclusions and suggested future works are summarized in chapter 8.

Chapter 2

Heat Transfer

To understand the phenomenon that is causing the heating of the electronic devices, we need to know the basics of the heat transfer. This chapter is an introduction to the fundamentals of heat transfer and thermal equations. Heat transfer mechanisms are examined and the governing heat transfer equations are introduced. For the measurement temperature distribution accurately over the device, fundamentals of heat transfer are inevitable.

2 Heat Transfer

In general, Heat Transfer or *Heat* is defined as “the energy in transit due to a temperature difference” [12].

There are two major mechanisms of heat transfer, *Conduction and Radiation*, which occur in solids and fluids. However if heat transfers from a solid surface to a moving fluid by conduction, it is known as *Convection* [13].

2.1 Heat Conduction

When heat is transferred within a material due to molecular vibration, it is called *Conduction*. For instance, heat is transferred into a metal rod from one end to the other due to the temperature difference.

2.1.1 Fourier's Law

According to *Fourier's law*, the amount of heat transferred by conduction in a one-dimensional plane per unit time can be expressed as equation (2.1), where k (W/mK) is the thermal conductivity and T is temperature in K [13].

$$q_x = -k \frac{dT}{dx} = -k \nabla T \quad (2.1)$$

Where:

$q = \frac{dQ}{dT}$ (W) is the rate of heat energy transporting in x direction by conduction,

k (W/m.K) is the thermal conductivity of medium material,

A (m²) is the area through which heat energy flows and its normal to the transfer direction x ,

T (K) is the temperature of material at location x ,

and x (m) is the location variable.

The negative sign indicates that heat is transferred in the direction of decreasing temperature.

Figure (2.1) shows that plate surface temperatures are T_1 and T_2 ; assuming T_1 is greater than T_2 . In this example heat is transferred only by conduction in x direction. Temperature differences in y and z directions are assumed to be zero.

Figure 2.1: 1D conduction heat transfer in a plate $T_1 > T_2$; $q_y=0$ and $q_z=0$ [13].

2.1.2 Thermal Conductivity

Thermal conductivity, k , is a thermo-physical property of materials. It represents the rate of conduction heat transfer per unit area for a temperature gradient of 1°C/m . It has SI units of $\text{W/m}^\circ\text{C}$ [13].

Most materials have a thermal conductivity that varies with temperature. A constant thermal conductivity can be assumed for a substance if its temperature variations are small. Figure (2.2) shows the thermal conductivity of different materials versus temperature variations.

Figure 2.2: Thermal Conductivity of different materials versus temperature [13].

In case of semiconductors, a nonlinear thermal conductivity variable with temperature is considered, equation (2.2).

$$K(T) = K(T_0) \left[\frac{T}{T_0} \right]^n \quad (2.2)$$

Where $n = -1.25$ for Silicon [14].

2.1.3 Heat Capacity

Heat Capacity, c , is the quantity that represents the amount of heat required to change one unit of mass of substance by one degree. The SI units of heat capacity are J/Kg 0 K [13].

$$Q = mc\Delta T \quad (2.3)$$

Where Q is the heat energy received or given out by the substance, m is the mass of the substance, and ΔT is the change in temperature.

Heat capacity is often expressed in a constant volume, C_v , or a constant pressure, C_p . A heat source can be either internal or external in a heat transfer system. Transistors, resistors and semiconductor chips are good examples of internal heat sources. Examples of external heat sources are different types of cooling systems such as fans and fins in power devices.

Considering heat is transferred only by conduction, heat sources are all internal and thermal conductivity is temperature dependent, by applying Fourier's law, time dependent heat transfer equation is defined as follows:

$$\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot (-k \nabla T) = Q \quad (2.4)$$

Where T (0 K) is temperature, t (s) is time, ρ (kg/m 3) is density, and C_p (J/Kg 0 K) is specific heat capacity. Q (W/m 3) is the heat source or heatsink density; depending on the heating or cooling behavior, it is positive or negative respectively.

2.2 Heat Radiation

Heat Radiation is an exchange of temperature between two surfaces with different temperature via electromagnetic waves [13]. Figure (2.3) illustrates electromagnetic spectrum for thermal radiation wavelength band.

Figure 2.3: Thermal Radiation Portion for Electromagnetic Spectrum [14].

The medium through which thermal radiation passes can be a vacuum or a transparent gas, liquid or solid. Objects within the path of heat radiation *absorb*, *reflect* and in case of transparent materials, *transmit* these electromagnetic waves. Absorptivity α , reflectivity ρ , and transmissivity τ , of a body represent how much a body absorb, reflect and transmit in the presence of thermal radiation. These parameters (α , ρ and τ) depend on the material of the body and the temperature of the emitting source [13].

$$\alpha + \rho + \tau = 1 \quad (2.5)$$

2.2.1 Stefan-Boltzmann Law

According to Stefan-Boltzmann law, the total emissive power, E_b , for a blackbody is the total rate of thermal radiation emitted by a perfect radiator per unit surface area [13].

$$E_b = \sigma T_s^4 \quad (2.6)$$

A blackbody is an object that absorbs all the radiant energy reaching its surface, $\alpha = 1$, where σ is Stefan-Boltzmann constant and T_s is the absolute surface temperature.

For non-blackbody surfaces the total emissive power is generally given in the following form:

$$E = \epsilon E_b = \epsilon \sigma T_s^4 \quad (2.7)$$

Where the emissivity (ϵ) can have a value between zero and one.

The total radiative heat flux that arrives at a body is called *irradiation*, G . The thermal irradiation received by a surface is disturbed as follows (see Figure 2.3):

Thermal radiation flux absorbed = αG

Thermal radiation flux reflected = ρG

Thermal radiation flux transmitted = τG

Considering an opaque surface, the total radiative heat flux that leaves the body is called *radiosity*, J [12].

$$J = \rho G + \epsilon \sigma T^4 \quad (2.8)$$

Therefore the net radiative heat flux into the body is obtained according to equation (2.9).

$$q = G - J \rightarrow q = (1 - \rho)G - \epsilon \sigma T^4 \quad (2.9)$$

If the surface is diffusive-gray (gray body is a surface whose emissivity is independent of the electromagnetic wavelength) and opaque then the net radiative heat flux into a boundary is:

$$\rho = \epsilon \rightarrow q = \epsilon(G - \sigma T^4) \quad (2.10)$$

Consequently, heat transfer equation is defined as in equation (2.11), when heat is transferred by conduction and radiation.

$$\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot (-k \nabla T) = Q + \epsilon(G - \sigma T^4) \quad (2.11)$$

Where Q is the heat energy received or given out by the substance,

ΔT is the change in temperature,

$T (^{\circ}K)$ is temperature,

ρ (kg/m^3) is density,

C_p ($J/Kg^{\circ}K$) is specific heat capacity.

2.3 Heat Convection

When a fluid flows over a solid, with different temperature than the solid, the process of heat transfer is called Convection. Heat Convection is generally the conduction mechanism of heat transfer when the heat source is external; therefore, heat conduction mechanism of heat conduction has primary role in heat convection.

2.3.1 Newton's Law of Viscosity

Newton's Law of Viscosity describes the velocity of a flowing liquid. Newton viewed laminar flow as the behavior of a liquid separating two solid parallel plates [12] as

$$\mu = \frac{Fy}{Au} \quad (2.12)$$

Where μ is the viscosity (kg/ms), F is the shear force (Kg.m/s²), y is the distance between the plates (m), A is the area of each plate (m²), and u is the fluid velocity, (m/s).

Therefore, the shear stress is defined as:

$$\tau = \frac{dF}{dA} = \mu \frac{\partial u}{\partial y} \quad (2.13)$$

2.3.2 Newton's Law of Cooling

Newton's law of cooling states that the rate of cooling of an object is proportional to the temperature difference between the object and its surroundings [12].

$$\frac{dT}{dt} = -k(T - T_a) \quad (2.14)$$

In equation (2.14), T_a is the ambient temperature, T is the temperature of the solid and k is appositve constant.

Applying Newton's law, the local convection heat flux of a fluid passing over a surface is expressed as:

$$q'' = h(T_s - T) \quad (2.15)$$

Where T_s is the surface temperature and h is the local convection coefficient.

Since the heat convection coefficient and local heat flux vary by the flow conditions, the total heat flux rate is defined as follows:

$$q = \int_{A_s} q'' dA_s \quad (2.16)$$

This leads to another way of expressing total heat flux, equation (2.17).

$$q = H(T_s - T) \quad (2.17)$$

Where H is the *mean coefficient of heat transfer*. It has SI units of (W/ (m² °K)). It depends on flow regions, fluids and thermodynamic conditions.

Therefore, heat transfer equation is defined as follow (considering heat is transferred by all types of the above mechanisms) [15]:

$$\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot (-k \nabla T) = Q + \varepsilon(G - \sigma T^4) + h(T_s - T) \quad (2.18)$$

Where $\rho C_p \frac{\partial T}{\partial t}$ represents the rate of energy increase in the solids, $-K \nabla T$ is the heat conduction term, and the right side of the equation represents the heat generation amount in the system.

For most electronic component, heat conduction is the most important heat transfer phenomenon; therefore most researchers consider a component that has thermal conduction as its only mode of internal heat transfer. Therefore, equation (2.18) can be expressed as:

$$\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot (-k \nabla T) = Q \quad (2.19)$$

2.4 Summary

Heat Transfer mechanisms (Conduction, Convection and radiation) and governing equations are introduced. For most electronic component, heat conduction is the most important heat transfer phenomenon; therefore most researchers consider a component that has thermal conduction as its only mode of internal heat transfer.

Chapter 3

Thermal Mapping

This chapter is brief introduction to Thermal Mapping and recent advances that have taken place related to thermal mapping techniques. In this research we have performed thermal mapping on printed circuit board by optical method. The purpose of monitoring the temperature is to obtain an image of the thermal map of its surface. This thermal map can cover the entire surface or merely a region of it. It can be continuous (with a given lateral resolution) or discrete (temperature at finite and specific number of points of the surface: punctual measurements). Thermal monitoring techniques can be categorized into three main groups: optical techniques, mechanical techniques and built-in temperature sensors.

Optical methods can be classified in methods that require a coating (liquid crystals, microscopic fluorescence) and those which take measurements on the sample surface, without any coating (infrared emission, thermoreflectometers, interferometers). Mechanical methods include techniques based on mechanical contact between the sensor and the surface to be measured. This category includes the atomic force microscopy, with different tips: thermocouples, Pt resistors. Finally, temperature can be measured with electronic sensors built-in with the CUT (Circuit under Test). These sensors are based on the temperature dependency of the electrical characteristics of semiconductor devices. The output signal of built-in temperature sensors can be proportional either to absolute temperature or to the difference in temperature at two points on the silicon surface. This leads to the categorization of temperature sensors into two groups: absolute and differential.

The electrical output signal of a sensor can be written for the absolute and differential categories as:

$$\text{Signal Out} = S_A T + C \quad (\text{Absolute}) \quad (1)$$

$$\text{Signal Out} = S_D (T_2 - T_1) \quad (\text{Differential}) \quad (2)$$

Where S_A is the absolute sensitivity of the absolute temperature sensor, S_D the differential sensitivity of the differential temperature sensor, C an offset constant that may be zero and T , T_2 and T_1 are temperatures at different points on the silicon surface [16]. Absolute temperature sensors are used to monitor the working temperature of the CUT and eventually correct its operating point if it is working beyond its reliability limit [17]. Differential temperature sensors are used to detect alterations of the thermal map of the silicon due to changes in the power dissipated by its devices. They are insensitive to temperature increases that may offset the thermal map of the silicon surface, e.g. ambient temperature changes or leakage current increases in CMOS circuits.

Thermal Mapping methods can be classified in another way as contact and non contact thermal mapping methods. Mechanical and Built-in temperature sensors fall in the category of contact thermal mapping methods and optical techniques are the non contact methods.

3.1 Contact Thermal Mapping Methods

In contact methods, either a device or a film is physically in contact with the surface of the device on which temperature is measured [18]. Typical devices are thermistors [16] or thermocouples [19], which are placed as a probe for a scanning thermal microscope (SThM, which, in fact, is an atomic force microscope). Liquid crystal thermography and Fluorescent microthermography are two well known contact thermal mapping methods.

3.1.1 Scanning Thermal Microscopy

Scanning Thermal Microscope is a conventional atomic force microscope (AFM) mounted with a specific probe. The AFM system allows us to control the tip position and contact force with the sample. Monitoring is performed with a feedback loop between the signals of three x-y-z piezo-electrical ceramics carrying the tip cantilever and four photodiodes tracking a laser beam, which reflects on the probe. The probe is a Wollaston wire shaped as a tip and etched to uncover the core platinum wire in figure (3.1).

Figure 3.1: Schematic of thermal Probe [16].

The Pt (platinum) wire is used as a thermal resistor: at constant input current, the tip voltage is measured while scanning the surface so that the Pt electrical resistance can be estimated at each point on the sample surface. The AFM is used in contacting mode therefore thermal equilibrium is achieved between the probe and the surface. A preliminary calibration allows us to relate temperature variations to electrical resistance variations to accuracy within 10%. The contact radius of the tip can be estimated to 50 nm, its diameter being 5 mm. A laser beam reflects on the mirror to detect z-deflections of the cantilever with nanometric precision, allowing us to extract topographic maps of the IC surface.

Figure (3.2) shows measurements performed with the SThM. (a) shows a processed topographic image while a photograph of the same location of the layout is provided in (b). Higher sensitivity is observed in phase measurements than in amplitude AC or DC measurements. Note that the metal line, which acts as a heat spreader, attenuates both the phase and amplitude signals. The time needed to extract these images is about 2 min. The duration of the scanning per unit area depends on the resolution. For instance, if the image size is set to: $50 \times 50 \text{ mm}^2$ divided into 200 lines and one line being scanned in 1s, the scanning rate is 16 s/mm^2 and the total scanning time is of course of the order of 3 min. The SThM set-up affords a high spatial resolution for heat source tracking. After scanning the zone under interest, the probe can be positioned to a set of points in order to improve the averaging and filtering of local measurements.

Figure 3.2: Topographic and AC temperature measurements [16].

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3.1.2 Liquid Crystal Thermography

Computer-controlled, automatic equipment has been developed for the thermal mapping of IC chips, based on observing the nematic/isotropic phase transition of liquid crystals [20]. This phase transition occurs at a T_{phT} characteristic temperature and produces a sharp contour between the surface regions below T_{phT} and above T_{phT} if we observe in a polarizing microscope the LC coated surface of the chip. Such a microscopic image is shown in figure (3.3). The IC surface is observed by a conventional (visible range) black and white CCD (Charged coupling Device) camera mounted onto the microscope which can be seen in figure (3.4). The good quality of TV camera is of greater importance. High resolution and low noise are demanded. The optical properties of nematic and isotropic are strongly different. A disadvantage is that we have only one isotherm in contrary to the cholesteric crystals where set of colors appear which maps a number of temperatures.

Since sample preparation is time consuming process by using a set of crystals with different T_{pt} values is not a practical solution, only one crystal and changing and controlled ambient temperature will be used. The histogram is a diagram giving the number of occurrence of the pixels with different brightness values. The x axis is the brightness, beginning from the black, ending on the white, while the y axis is the occurrence. Such a histogram is plotted in figure (3.3) under the image it refers to.

Figure 3.3: (a) Polarized microscopic picture of the LC measuring equipment, before processing, and (b) the histogram of the same picture.

In the polarizing microscope the isotropic regions seem to be dark while the nematic areas show a blurred image with rainbow-like fringes. The first task is to separate clearly the two regions. The image processing method that is suitable to achieve this goal is called *thresholding*. The threshold is a well-chosen brightness value. Below this value the

picture will be black whereas the other areas will be white. This procedure results in a *binary image*.

A suitable solution can be obtained to find the best threshold value. Following our practice, a suitable solution can be obtained with the help of the *histogram* of the picture. We can observe that the black area produces a sharp maximum in the left-hand side of the histogram and the lighter area causes a broader maximum. Searching the minimum on the histogram between these two peaks gives an appropriate threshold value. Recording of the different isotherms can be realized by changing the ambient temperature during the LC measurement. A computer-controlled thermostat mounted on the microscope stage is suitable for this goal [20]. Figure (3.4) represents the setup for LC thermal mapping system as explained in this section.

Figure 3.4: Unit of LC Thermal Mapping System [20].

If the actual temperature of the thermostat is T_{TH} and the phase transition of the LC occurs at T_{phT} then the contour of the phase transition belongs to the temperature rise.

$$\Delta T = T_{phT} - T_{TH} \quad (3.1)$$

This ΔT rise is caused by the dissipation of the chip. The package temperature is set by a thermostat, which is interfaced to the controlling PC by Thermostat driver circuit.

3.1.3 Fluorescent Microthermography

Light from 100W Hg arc lamp is passed through blue-glass filters and a 0.25-m monochromator and is brought to a focus on sample at an oblique angle. Light from arc lamp H is collected by lens L_1 , passed through blue filters BG and monochromator M , and focused by lens L_2 onto sample S . The image is relayed by lenses L_3 and L_4 onto the camera CCD, through fluorescence line filter IF . The exit slit of the monochromator is removed, causing uniform illumination of the sample at an intensity of $700 \mu\text{W}/\text{cm}^2$ in a wavelength band 345-380 nm, as measured with a calibrated photodiode (the monochromator is unnecessary, but it was convenient to leave it in existing optical setup). Using two camera lenses and a 612-nm interference filter, the specimen is imaged with magnification 4.4 onto the CCD camera chip. The CCD, Fairchild model 202, consists of a rectangular, 100 X 100 array of photodiodes on $30 \times 40 \mu\text{m}$ centers; the short dimension of each resolution element (pixel) in the sample image is thus $6.8 \mu\text{m}$. The F202 CCD is an interline transfer device which needs no shutter. The chip is clocked out by hard-wired sequencer, which reads alternate odd-even row half-frames. The camera is controlled by an LSI-11/23 microcomputer, which writes images onto a compact or floppy disk. The observed resolutions of 0.01°C and $15 \mu\text{m}$ should be straightforward to improve. These measurements could be made and displayed automatically by a low-cost, compact, hard-wired instrument. As an indication of the potential utility of such measurements to integrated circuit design and testing, the capability to make detailed conclusions about the regions of local power dissipation in devices can be demonstrated. In order to remove spatial variations in fluorescence imaging, hot and cold images should be digitally divided. That is, brightness of each pixel is proportional to the logarithm of the ratio of the brightness of that pixel in the cold image to that in the hot image and is thus proportional to the temperature difference there. This normalization procedure removes all traces of spatial brightness variations due to the optical properties of the fluorescent film, the specimen, the optics, and the CCD, leaving purely a thermal image. The procedure is carried out offline by a computer program that performs the sequence of picture operations.

$$\left[\frac{S \sum_i (C_i - B)}{S \sum_i (H_i - B)} \right]^{-1} \quad (3.2)$$

Where C_i and H_i are the cold and hot images, B is a bias image and S is the 1.5- pixel convolution operation. Automated Windowing and stretching are used for contrast enhancement in all the images here.

3.2 Non Contact Thermal Mapping Methods

In non contact methods, neither a device nor a film is physically in contact with the surface of the IC or the device of which temperature is measured. Interferometry, Thermo reflectance and Infrared thermography are mainly optical thermal mapping techniques used for investigation of temperature distribution on PCB, ICs and devices.

3.2.1 Interferometry

Interferometry is an optical thermal mapping technique commonly used. One laser probe is a high resolution Michelson interferometer [24] as shown in figure (3.6). The laser is a stabilized, polarized HeNe laser ($\lambda = 632.8 \text{ nm}$). The beam splitting element of the interferometer is a polarizing prism.

Figure 3.6: Schematic View of Laser Probe [24].

By rotating a half-wave plate ($\lambda/2$) in the incoming laser beam, it is possible to partition the intensity of the reference arm to that of the probe arm so as to equalize the reflected intensities and obtain high contrast interference fringes. In the reference and probe arm, a quarter-wave plate ($\lambda/4$) is inserted. The linear polarization of the incoming light is rotated by 90° when coming out as it has passed the quarter-wave plate twice. This allows all the intensity of the returning beams to be reflected onto the photo detector while the polarizing prism acts as an optical insulator. The two beams have orthogonal linear polarizations. To obtain interferences, both polarizations are projected at 45° upon a single axis by passing through a polarized beam splitter before passing through the photo detector.

A microscope objective focuses the probe beam upon the surface of the component under test. The phase of the reflected beam is modulated by the normal surface displacements. The sample is mounted on a three-dimensional micrometric translation stage. The laser impact upon the sample can be viewed on a CCD camera by moving the mirror in front of the reflected probe beam and reducing the laser beam intensity with the attenuation placed in the laser beam. The lateral resolution is better than $1 \mu\text{m}$. The interferometer is actively stabilized at the point of highest sensitivity (mid-fringe).

The detected signal is averaged in synchronism with the excitation signal and recorded by a digital oscilloscope or by a lock-in amplifier for small ac signal measurements. The absolute values of the surface displacement are obtained from the comparison of the photo detected signal amplitude with the fringe signal amplitude from large displacements produced by moving the piezomirror in the reference arm. The equipment allows us to measure the surface temperature locally through the dynamic deformation of the IC surface. The experimental sensitivity of the bench is obtained by measuring the normal surface displacement due to the Joule effect heating of a resistive layer upon an IC as a function of the electrical current amplitude going through it.

The results are shown in figure (3.7). The amplitude of the displacement is plotted on a logarithmic scale. A slope of two is the signature of the quadratic dependency of the normal surface displacement amplitude versus current. The signal is detected down to amplitudes as small as a fraction of a femometer (10^{-15} m), which is the shot noise detector limit.

Figure 3.7: Experimental sensitivity of Interferometer [24].

3.2.2 Thermoreflectance

Thermoreflectance is the variation of the reflection coefficient of a material with temperature [22-23].

$$R(T) = R_0 + \Delta R(T) = R_0(1 + k\Delta T) \quad (3.3)$$

Where R is the thermal resistance at temperature T , R_0 is the resistance at ambient temperature and k is the emissivity of the material. If we focus a laser beam of intensity Φ_0 onto the material and detect with a photodiode the reflected light intensity $R\Phi_0$, variations of

the current I generated can be related to variations in the temperature T (ΔT) of the area targeted by the laser.

$$\Delta T = k \frac{\Delta I}{I} \quad (3.4)$$

It can be observed that with a simple optical probe, it is possible to measure dynamic temperature changes of normally working ICs. Absolute values can be readily obtained if $k = (1/R) (\partial R / \partial T)$, the relative reflectance temperature coefficient, is known. For pure silicon, the value of $k = 1.5 \times 10^{-4}$ is given by literature [25] and we found by a specific calibration procedure 1.35×10^{-4} and 2.5×10^{-5} for Al [18]. The experimental setup is the same as the one described in figure (3.6) with the difference that no light is sent to the reference arm. No interferences occur and the detector measures amplitude changes of the reflected laser beam. It can be shown that the device is a simple and excellent tool for IC surface temperature variation measurements. The optical probe is capable of measuring surface temperature changes in the range 10^{-3} – 10^2 K at a micrometric scale upon ICs.

High resolution temperature mapping is possible and dynamic responses can be studied in the dc 125-MHz range with the photodetection system. The upper limit of 125 MHz is due to the bandwidth of the present electronic circuitry that reads the current generated by the photodiode. One application for laser optical methods is temperature measurement: Figure (3.8) shows the result obtained by scanning a laser beam across an IC where some components are running. The left-hand side of this figure shows the reflectance results with a 3- μ m step, two aluminum metal lines; A and B can clearly be seen. The right hand side shows the relative reflectance change between on and off. The method allows very small temperature changes to be determined as the scale covers a range from 0°C to 6°C.

Figure 3.8: Thermal Mapping on IC [24].

3.2.3 Infrared Thermography

Thermal mapping method by using Infrared Camera for several PCBs and integrated circuits has been proposed by several researchers. To generate an accurate thermal map for a given chip, we need to measure the temperature at multiple points. To do so, an infrared camera is used to measure temperature as close as possible to the transistor junction. Infrared thermography transforms the thermal energy, emitted by objects in the infrared band of the electromagnetic spectrum, into a visible image. It is known that an object at a temperature above absolute zero (-273°C) emits electromagnetic radiation in the form of rays that fall into the infrared (IR) portion of the electromagnetic spectrum, i.e. from 1 to $1000\text{ }\mu\text{m}$. This energy is generally emitted from about $2.5 \times 10^{-5}\text{ mm}$ of the object surface and cannot be seen by the unaided eye. Infrared thermography (IRT) is a non-contact, non-intrusive technique, which enables us to see thermal energy. In fact, a radiometer transforms the energy radiated from objects in the infrared band of the electromagnetic spectrum into an electronic video signal and ultimately into a visible image; each energy level may be represented by a color, or a grey level. The energy emitted by a body is mainly a function of its surface temperature and so infrared thermography may be considered as a two-dimensional technique of temperature measurement.

The core of the equipment is an infrared ($\lambda = 2\text{...}12\text{ }\mu\text{m}$) camera with its infrared detector cooled to an extremely low temperature to eliminate noise. It usually scans the image mechanically, using rotating mirrors or prisms. It requires special objectives that are transparent to infrared light. Infrared thermography can obtain a high temperature resolution usually on the order of 0.1°C . The accuracy is a bit worse because of the uncertainty of the surface thermal emissivity factor. Using black paint to coat the chip surface makes an accuracy of 0.2°C to 0.3°C realistic. The spatial resolution is on the order of 10 mm . The method is very fast, and can investigate even transient phenomena. Figure (3.9) shows some of the Infrared Camera pictures of Athlon64 core.

Figure 3.9: IR images of Athlon64 core.

The technique of Infrared thermography will be discussed in detail in the next chapter, as it is the prime focus of this research.

3.3 Summary

The dynamic evolution of the temperature on the surface of an IC is a projection of the circuit's behavior and IC structure. In this chapter, all contact and non contact methods have been discussed briefly. Non contact methods are preferred compared to contact methods, as they will not affect any normal operation of integrated circuit. Moreover, the accuracy that one can achieve with optical methods can never be achieved by any contact method.

Infrared thermography is chosen in this research as thermal mapping technique. This is one of the most popular experimental methods used in today's product design test process of industry.

Chapter 4

Infrared Thermography and its Different Setups

In this chapter, the basic principles of Infrared thermography will be introduced and different setups for thermography will be also discussed. The origin of infrared thermography comes from the early 1800s when the English physicist William Herschel discovered thermal radiation outside the deep red in the visible spectrum, the *invisible light* later called *infrared*. From this observation and the studies of many other scientists (amongst them Macedonio Melloni, Gustav Kirchhoff, James Clerk Maxwell, Joseph Stefan, Ludwig Boltzmann, Max Planck) in successive years, infrared thermography has become a useful technique of surface temperature mapping. Infrared thermography basically includes a camera, equipped with a series of changeable optics, and a computer. The core of the camera is the infrared detector, which absorbs the IR energy emitted by the object (whose surface temperature is to be measured) and converts it into electrical voltage or current.

4.1 Principles of Infrared Thermography

The subjects of infrared radiation and the related technique of thermography are still new to many who will use an infrared camera. The electromagnetic spectrum is divided arbitrarily into a number of wavelength regions, called *bands*, distinguished by the methods used to produce and detect the radiation. There is no fundamental difference between radiations in the different bands of the electromagnetic spectrum. They are all governed by the same laws and the only differences are those due to differences in wavelength.

Figure (4.1) illustrates the complete electromagnetic spectrum. Thermography makes use of the infrared spectral band. At the short-wavelength end the boundary lies at the limit of visual perception, in the deep red. At the long-wavelength end it merges with the microwave radio wavelengths, in the millimeter range.

Figure 4.1: Electromagnetic Spectrum [27].

The infrared band is often further subdivided into four smaller bands, the boundaries of which are also arbitrarily chosen. They include: the near infrared ($0.75\text{--}3\ \mu\text{m}$), the middle infrared ($3\text{--}6\ \mu\text{m}$), the far infrared ($6\text{--}15\ \mu\text{m}$) and the extreme infrared ($15\text{--}100\ \mu\text{m}$). Although the wavelengths are given in μm (micrometers), other units are often still used to measure wavelength in this spectral region, *e.g.* nanometer (nm) and Ångström (Å). The relationship between the different wavelength measurements is:

$$10\,000\ \text{Å} = 1000\ \text{nm} = 1\ \mu = 1\ \mu\text{m} = 0.000001\ \text{cms} \quad (4.1)$$

4.2 Blackbody Radiation

A blackbody is defined as an object that absorbs all radiation that impinges on it at any wavelength. The apparent misnomer *black* relating to an object emitting radiation is explained by Kirchhoff's Law (after *Gustav Robert Kirchhoff*, 1824–1887), which states that a body capable of absorbing all radiation at any wavelength is equally capable in the emission of radiation [28].

The construction of a blackbody source is, in principle, very simple. The radiation characteristics of an aperture in an isotherm cavity made of an opaque absorbing material represents almost exactly the properties of a blackbody. A practical application of the principle to the construction of a perfect absorber of radiation consists of a box that is light tight except for an aperture in one of the sides. Any radiation that then enters the hole is scattered and absorbed by repeated reflections so only an infinitesimal fraction can possibly escape. The blackness that is obtained at the aperture is nearly equal to a blackbody and almost perfect for all wavelengths. By providing such an isothermal cavity with a suitable heater it becomes what is termed a *cavity radiator*. An isothermal cavity

heated to a uniform temperature generates blackbody radiation, the characteristics of which are determined solely by the temperature of the cavity. Such cavity radiators are commonly used as sources of radiation in temperature reference standards in the laboratory for calibrating thermographic instruments, such as a FLIR Systems camera.

If the temperature of blackbody radiation increases to more than 525 °C (977 °F), the source begins to be visible so that it appears to the eye no longer black. This is the incipient red heat temperature of the radiator, which then becomes orange or yellow as the temperature increases further. In fact, the definition of the so-called *color temperature* of an object is the temperature to which a blackbody would have to be heated to have the same appearance. Now let us consider three expressions that describe radiation from emitted from a blackbody.

4.2.1 Planck's Law

Max Planck (1858–1947) was able to describe the spectral distribution of the radiation from a blackbody by means of the following formula:

$$W_{\lambda b} = \frac{2\pi hc^2}{\lambda^5 (e^{\frac{hc}{\lambda kT}} - 1)} \times 10^{-6} [\text{watt} / \text{m}^2] \quad (4.2)$$

Where $W_{\lambda b}$ is blackbody spectral radiant emittance at wavelength λ ,

c velocity of light = $3.8 \times 10^{-8} \text{ m/s}$,

h is Planck's constant = 6.6×10^{-34} Joule sec,

k is Boltzmann's constant = 1.4×10^{-23} Joule/K,

T is absolute temperature of a blackbody and

λ is the wavelength in μm .

This formula is valid for wavelength $\lambda > 0$. Planck's formula, when plotted graphically for various temperatures, produces a family of curves. Following any particular Planck curve, the spectral emittance is zero at $\lambda = 0$, then increases rapidly to a maximum at a wavelength $\lambda_{\max}$ and after passing it, approaches zero again at very long wavelengths ($\lambda \geq 3000\text{nm}$). The higher the temperature, the shorter the wavelength at which maximum occurs. Blackbody spectral radiant emittance according to Planck's law, plotted for various absolute temperatures is shown in figure (4.2).

Figure 4.2: Blackbody spectral radiant emittance according to Planck's law [28].

4.2.2 Wien's Law

By differentiating Planck's formula with respect to λ , and finding the maximum, one can obtain:

$$\lambda_{\max} = \frac{2898}{T} \mu\text{m} \quad (4.3)$$

This is Wien's formula (after *Wilhelm Wien*, 1864–1928), which expresses mathematically the common observation that colors vary from red to orange or yellow as the temperature of a thermal radiator increases. The wavelength of the color is the same as the wavelength calculated for $\lambda_{\max}$. Thus, a very hot star such as Sirius (11 000 K),

emitting bluish-white light, radiates with the peak of spectral radiant emittance occurring within the invisible ultraviolet spectrum, at wavelength $0.27\ \mu\text{m}$. The sun (approx. 6000 K) emits yellow light, peaking at about $0.5\ \mu\text{m}$ in the middle of the visible light spectrum.

At room temperature (300 K) the peak of radiant emittance lies at $9.7\ \mu\text{m}$, in the far infrared, while at the temperature of liquid nitrogen (77 K) the maximum of the almost insignificant amount of radiant emittance occurs at $38\ \mu\text{m}$, in the extreme infrared wavelengths.

4.2.3 Stefan-Boltzmann's Law

By integrating Planck's formula from $\lambda = 0$ to $\lambda = \infty$, we obtain the total radiant emittance (W_b) of a blackbody:

$$W_b = \sigma T^4 [\text{watt} / \text{m}^2] \quad (4.4)$$

This is the Stefan-Boltzmann formula, which states that the total emissive power of a blackbody is proportional to the fourth power of its absolute temperature. Graphically, W_b represents the area below the Planck curve for a particular temperature. It can be shown that the radiant emittance in the interval $\lambda = 0$ to λ_{max} is only 25 % of the total, which represents about the amount of the sun's radiation which lies inside the visible light spectrum. Using the Stefan-Boltzmann formula to calculate the power radiated by the human body, at a temperature of 300 K and an external surface area of $2\ \text{m}^2$, 1 kW power is obtained. This power loss could not be sustained if it were not for the compensating absorption of radiation from surrounding surfaces, at room temperatures which do not vary too drastically from the temperature of the body – or, of course, the addition of clothing.

4.2.4 Non Blackbody Emitters

So far, only blackbody radiators and blackbody radiation have been discussed. However, real objects almost never comply with these laws over an extended wavelength region – although they may approach the blackbody behavior in certain spectral intervals. For example, a certain type of white paint may appear perfectly *white* in the visible light spectrum, but becomes distinctly *gray* at about $2\ \mu\text{m}$, and beyond $3\ \mu\text{m}$ it is almost *black*. There are three processes which can occur that prevent a real object from acting like a blackbody: a fraction of the incident radiation α may be absorbed, a fraction ρ may be reflected, and a fraction τ may be transmitted. Since all of these factors are more or less wavelength dependent, the subscript λ is used to imply the spectral dependence of their definitions. Thus:

- The spectral absorptance α_λ = the ratio of the spectral radiant power absorbed by an object to that incident upon it.
- The spectral reflectance ρ_λ = the ratio of the spectral radiant power reflected by an object to that incident upon it.
- The spectral transmittance τ_λ = the ratio of the spectral radiant power transmitted through an object to that incident upon it.

The sum of these three factors must always add up to the whole at any wavelength, so we have the relation:

$$\alpha_\lambda + \rho_\lambda + \tau_\lambda = 1 \quad (4.5)$$

For opaque materials $\tau_\lambda = 0$ and the relation simplifies to:

$$\alpha_\lambda + \rho_\lambda = 1 \quad (4.6)$$

Another factor, called the emissivity, is required to describe the fraction ϵ of the radiant emittance of a blackbody produced by an object at a specific temperature. Thus, we have the definition:

The spectral emissivity ε_λ is equal to the ratio of the spectral radiant power from an object ($W_{\lambda 0}$) to that from a blackbody ($W_{\lambda b}$) at the same temperature and wavelength. Expressed mathematically, this can be written as the ratio of the spectral emittance of the object to that of a blackbody as follows:

$$\varepsilon_\lambda = \frac{W_{\lambda 0}}{W_{\lambda b}} \quad (4.7)$$

Generally speaking, there are three types of radiation source, distinguished by the ways in which the spectral emittance of each varies with wavelength.

- A blackbody, for which $\varepsilon_\lambda = \varepsilon = 1$.
- A graybody, for which $\varepsilon_\lambda = \varepsilon = \text{constant less than } 1$.
- A selective radiator, for which ε varies with wavelength.

According to Kirchhoff's law, for any material the spectral emissivity and spectral absorptance of a body are equal at any specified temperature and wavelength. That is:

$$\varepsilon_\lambda + \rho_\lambda = 1 \quad (4.8)$$

For highly polished materials ε_λ approaches zero, so that for a perfectly reflecting material (*i.e.* a perfect mirror) we have:

$$\rho_\lambda = 1 \quad (4.9)$$

For a gray body radiator, the Stefan-Boltzmann formula becomes:

$$W = \varepsilon \sigma T^4 [\text{Watt} / \text{m}^2] \quad (4.10)$$

This states that the total emissive power of a gray body is the same as a blackbody at the same temperature reduced in proportion to the value of ε from the gray body.

4.3 The Measurement Formula

When viewing an object, the camera receives radiation not only from the object itself but also collects radiation from the surroundings reflected via the object surface. Both these radiation contributions become attenuated to some extent by the atmosphere in the measurement path. To this comes a third radiation contribution from the atmosphere itself. This description of the measurement situation, as illustrated in the figure below, is so far a fairly true description of the real conditions. What has been neglected could for instance be sun light scattering in the atmosphere or stray radiation from intense radiation sources outside the field of view. Such disturbances are difficult to quantify, however, in most cases they are fortunately small enough to be neglected. In case they are not negligible, the measurement configuration is likely to be such that the risk for disturbance is obvious, at least to a trained operator. It is then his responsibility to modify the measurement situation to avoid the disturbance e.g. by changing the viewing direction, shielding off intense radiation sources etc. Figure (4.3) is the schematic representation of the general thermographic measurement situation by Infrared camera.

Figure 4.3: A schematic representation of the general thermographic measurement situation. 1: Surrounding; 2: Object; 3: Atmosphere; 4: Camera [28].

The temperature measured by Infrared camera varies from -50°C to 350°C . Assume that the received radiation power W from a blackbody source of temperature T_{source} on

short distance generates a camera output signal U_{source} that is proportional to the power input (power linear camera). We can then write

$$U_{source} = CW(T_{source}) \quad (4.11)$$

Where C is constant. If the source is gray body with emittance ε , the received radiation would consequently be εW_{source} . We are now ready to write the three collected radiation power terms:

1 – Emission from the object = $\varepsilon \tau W_{obj}$, where ε is the emittance of the object and τ is the transmittance of the atmosphere. The object temperature is T_{obj} .

2 – Reflected emission from ambient sources = $(1 - \varepsilon) \tau W_{refl}$, where $(1 - \varepsilon)$ is the reflectance of the object. The ambient sources have the temperature T_{refl} .

3 – Emission from the atmosphere = $(1 - \tau) W_{atm}$, where $(1 - \tau)$ is the emittance of the atmosphere. The temperature of the atmosphere is T_{atm} .

It has here been assumed that the temperature T_{refl} is the same for all emitting surfaces within the half sphere seen from a point on the object surface. This is of course sometimes a simplification of the true situation. It is, however, a necessary simplification in order to derive a workable formula, and T_{refl} can – at least theoretically – be given a value that represents an efficient temperature of a complex surrounding. Note also that we have assumed that the emittance for the surroundings = 1. This is correct in accordance with Kirchhoff's law: All radiation impinging on the surrounding surfaces will eventually be absorbed by the same surfaces. Thus the emittance = 1. The total received radiation power can now be written in equation (4.12).

$$W_{tot} = \varepsilon \tau W_{obj} + (1 - \varepsilon) \tau W_{refl} + (1 - \tau) W_{atm} \quad (4.12)$$

We multiply each term by constant C of equation (4.12) and replace the CW products by corresponding U according to the same equation, and get equation 4.13.

$$U_{tot} = \varepsilon\tau U_{obj} + (1 - \varepsilon)\tau U_{refl} + (1 - \tau)U_{atm} \quad (4.13)$$

Solve the equation 4.13 for U_{obj}

$$U_{obj} = \frac{1}{\varepsilon\tau} U_{tot} - \frac{1 - \varepsilon}{\varepsilon} U_{refl} - \frac{1 - \tau}{\varepsilon\tau} U_{atm} \quad (4.14)$$

This is the general measurement formula used in all the FLIR Systems thermographic equipment. The voltages of the formula are: U_{obj} – Calculated camera output voltage for a blackbody of temperature T_{obj} i.e. a voltage that can be directly converted into true requested object temperature. U_{tot} – Measured camera output voltage for the actual case, U_{refl} – Theoretical camera output voltage for a blackbody of temperature T_{refl} according to the calibration and U_{atm} – Theoretical camera output voltage for a blackbody of temperature T_{atm} according to calibration. The operator has to supply a number of parameter values for the calculation:

- The object emittance ε .
- The relative humidity.
- Atmospheric Temperature, T_{atm} .
- Object distance (D_{obj}).
- The (effective) temperature of the object surroundings or the reflected ambient temperature T_{refl} .
- The temperature of the atmosphere T_{atm} .

This task could sometimes be a heavy burden for the operator since there are normally no easy ways to find accurate values of emittance and atmospheric transmittance for the actual case. The two temperatures are normally less of a problem provided the surroundings do not contain large and intense radiation sources. A natural question in this connection is: How important is it to know the right values of these parameters? Figure (4.4) represents the relative magnitude of radiation sources under varying conditions, which shows the importance of the discussed fact. It could though be of interest to get a feeling for this problem already here by looking into some different measurement cases and compare the relative magnitudes of the three radiations terms.

Figure 4.4: Relative Magnitude of Radiation Sources under varying conditions. 1: Object temperature; 2: Emittance; *Obj*: Object radiation; *Refl*: Reflected radiation; *Atm*: atmosphere radiation [28].

This will give indications about when it is important to use correct values of which parameters. We have finally to answer a question about the importance of being allowed to use the calibration curve above the highest calibration point, what we call extrapolation. Imagine that we in a certain case measure $U_{\text{tot}} = 4.5$ volts. The highest calibration point for the camera was in the order of 4.1 volts, a value unknown to the operator. Thus, even if the object happened to be a blackbody, i.e. $U_{\text{obj}} = U_{\text{tot}}$, we are actually performing extrapolation of the calibration curve when converting 4.5 volts into temperature.

Let us now assume that the object is not black, it has an emittance of 0.75, and the transmittance is 0.92. We also assume that the two second terms of Equation (4.14) amount to 0.5 volts together. Computation of U_{obj} by means of Equation (4.14) then results in $U_{\text{obj}} = 4.5 / 0.75 / 0.92 - 0.5 = 6.0$. This is a rather extreme extrapolation, particularly when considering that the video amplifier might limit the output to 5 volts! Note, though, that the application of the calibration curve is a theoretical procedure where no electronic or other limitations exist. We trust that if there had been no signal limitations in the camera, and if it had been calibrated far beyond 5 volts, the resulting curve would have been very much the same as our real curve extrapolated beyond 4.1 volts, provided the calibration algorithm is based on radiation physics, like the FLIR Systems algorithm. Of course there must be a limit to such extrapolations.

4.4 Infrared Thermography Setups

The thermally sensitive parameters vary according to the type of semiconductor used and, thus, vary according to the type of semiconductor used and thus would require a unique measurement setup and calibration procedure for systems using different types of semiconductor components [29]. There are several points to be considered for the experimental setup of the Infrared Thermography. Atmospheric temperature, Reflected Temperature, Emissivity, Distance of measurement, Relative humidity and the reference temperature. Different setups have been explained in the literature but all these conditions prevalent during the performance of experiment are not highlighted in their work.

All the above mentioned parameters need to be fed manually in the camera depending on the experimental conditions and setup. Using IR thermal measurement system requires a uniform emissivity value to compute the surface temperature of the device under test. This parameter is a function of both component material and surface finish. However, the systems being evaluated usually do not have such a uniform finish. Instead, the exposed surface often has a plethora of materials and finishes such as the polished silicon component die, gold plating for die attachment, wire bond materials, aluminum nitride substrate, etc. The spray coatings are used in this project to have uniform emissivity, which will be explained in detail in the next chapter.

For thermal mapping of integrated circuits, cooling of the device plays a very important role. In order to develop perfect thermal map on PCB or IC by making use of Infrared Camera we will need to develop Infrared transparent heatsink, so that it can remove heat effectively at very high cooling rates ($>1\text{W}/\text{cm}^2$ K). The reasons for the heatsink requirements are discussed in detail below:

First, high cooling rates allow measuring state of art, high power ICs and PCBs with power densities of larger than $100\text{ W}/\text{cm}^2$ at the specified operating conditions (right voltages, frequencies and chip temperatures). This is in particular important considering that the leakage power, which makes up for almost 50 % of the total power, is exponentially dependent on the chip temperature field [30].

Second, high cooling rates are essential to prevent the spreading of the heat throughout the Si die, which can diminish severely the potential spatial resolution and contrast of the measured thermal distribution. In order to illustrate this effect, the thermal distributions on circuitry level have been calculated for a generic power map as a function of cooling rate as shown in figure (4.5). The generic power map is shown in figure (4.5A) while figure (4.5B-F) show the respective temperature distributions for different cooling rates (B: 0.01 W/cm²K, C: 0.1 W/cm²K, D: 1 W/cm²K, E: 10 W/cm²K, F: 100 W/cm²K). The chip dimensions are 18 x 18 mm² with a die thickness of 750 μ m [30].

Figure 4.5: Temperature distributions on circuitry level as a function of cooling rate. The image A shows the underlying Power Distribution [30].

In the results of figure (4.5), the total power is adjusted in the chip so that the peak temperature on the die is always 100°C. As illustrated in Figure (4.5) for low cooling

rates, the temperatures are almost completely washed out, while the thermal distributions at higher cooling rates (Fig.4.5E and F) provide a much better spatial resolution and contrast and thus resemble the underlying power maps a lot better. A typical range of cooling rates, which are required to operate a state of the art, high power microprocessor under full operational conditions, is between 1 and 3 W/cm²K.

Finally and as a third reason for the importance of high cooling rates, since thermal time constants are cooling rate dependent, a non-realistic cooling rate would alter the whole temperature dynamics significantly and thus affect the processor operation and power consumption significantly. In summary, the high cooling rates of this transparent heatsink are not only important to avoid overheating and to observe temperature changes with the appropriate time constants, but they are also important to actually being able to observe some contrast in the across chip temperature distributions. Hence the significance of emissivity setting and heatsinks in Infrared Thermography of electronic circuits has been clearly explained [30].

4.4.1 Literature Review on Infrared Thermography Setups

The setup for infrared thermography was described by Mario J. Paniccia [30] at Intel Corporation in 2001. This setup proposes the method that permits the removal of heat from the back side of an integrated circuit semiconductor substrate while performing optical based testing through or at the back side surface of the semiconductor substrate. The electronic device is to be kept upside down as emissions from the back side of an integrated circuit may be measured to determine a variety of defects such as impact ionization, shorts, hot carrier effects, forward and reverse bias P-N junctions, transistors in saturation and gate oxide breakdown. Figure (4.6) shows the setup suggested in this patent. Heatsink is thermally coupled to the outer edges of the heat slug's top surface.

Figure 4.6: IR Thermography Setup [30].

Heat slug has to be infrared transparent, and so it is usually made of diamond as it is excellent conductor of heat and is infrared transparent also. But depending upon the application, the material used for the heat slug can be changed, i.e. sapphire, silicon, germanium and gallium arsenide etc. Heatsink includes metal plate (e.g. aluminum, copper). The only constraint that is binding for heatsink is that it has to have a large thermal mass and a large heat transfer area. Thermal grease or oil can be placed between heatsink and heat slug as a heat transfer medium to reduce thermal resistance at these interfaces. The electronic device is mounted on Pin Grid Array with the ball bonds.

In accordance with the present setup, infrared transparent heat slug is used to cool integrated circuit device as photons are being emitted from the operating device. In addition to providing a path for heat to escape from the backside surface of integrated circuit device, heat slug provides the free flow path between backside surface and camera for photons being emitted with a wavelength within the transmitted infrared spectrum.

Anti reflective coatings can be deposited at the junctions i.e. between heat slug and electronic device, between heat slug and heatsink, so as to reduce the losses due to reflection. The anti reflective coatings may be deposited onto one those respective surfaces using variety of known processes such as evaporation, electron-beam deposition and sputtering. There are other losses that incur which are absorption losses through silicon semiconductor substrate are exponentially functioning of the substrate thickness. By thinning the substrate these absorption losses can be greatly reduced to enhance the transmission of the light, photons and thermal radiation from the semiconductor substrate

surface. Semiconductor substrate is globally thinned and polished prior to the placing the infrared heat slug over the backside of the semiconductor device. In some cases it might not be necessary to test complete integrated circuit, so particular portion of the circuit should be thinned rather than the whole circuit.

Infrared Thermography setup was developed by James Lacy and Alan Weger [31] in 2006. A new setup was designed particularly for determining the temperature distribution on the chip. An IR transparent liquid flows through a micro-duct of a specifically designed cooling cell directly over the microprocessor die. The duct height as well as the flow speed can be adjusted, which allows for different cooling rates. Specifically, the cooling rates can be readily tuned between $0.2 \text{ W/cm}^2 \text{ K}$ all the way up to $4.0 \text{ W/cm}^2 \text{ K}$ depending on the choice of the fluid and flow conditions. In this setup, instead of Infrared Camera, Liquid N_2 cooled InSb array detector is used. The system on which experiment is performed is the microprocessor. The base plate is also kept to keep the device under test is at the same ground level. Figure (4.7) shows the implemented setup.

Figure 4.7: Spatially Imaging Technique and IR-transparent Cooling Cell [31].

Hendrik F. Hamann proposed the new method that provides real time temperature and power mapping of fully operating electronic devices [32]. The method utilizes infrared (IR) temperature mapping, while an IR- transparent coolant flows through a specially designed cell directly over the electronic device. In order to determine the chip power distributions the individual temperature fields for each heat source of a given power and

size on the chip (as realized by a scanning focused laser beam) are measured under the same cooling conditions. A heat source of given power and size (laser beam) is applied to bottom surface of the device.

Then the measured chip temperature distribution is represented as a superposition of the temperature fields of these individual heat sources and the corresponding power distribution is calculated with set of linear equations. Heat is the product of power dissipation within the device under operating conditions, and therefore heat increases in proportion to power. Figure (4.8) is cross sectional diagram of the system of electronic device being measured.

Figure 4.8: Cross section Diagram of the Setup [32].

It also shows the temperature detector, such as infrared camera and a duct. For example, in some cases it may be preferred to use thermal reflectance to monitor the temperature of the electronic device. Specifically, the photon detector detects the amount of reflected photons from the electronic device, which changes optical reflectivity with temperatures. Attached to the electronic device is the electronic device is heatsink, which includes the duct, formed by a duct wall above and the bottom part of the duct is typically the top surface of the electronic device. Within the duct is a fluid that flows over the top surface of the electronic device.

In one of the case, the duct wall of the duct and the fluid are at least semi-transparent to infrared radiation. This allows infrared camera to gather thermal information and position information to of the electronic device. The duct wall comprises of polished silicon, quartz, sapphire or diamond. Infrared camera captures thermal information of the top surface of the electronic device as function of position. Thus, the infrared camera captures and records thermal information and position information for each temperature reading. This allows the generation of a thermal profile of the top surface of the electronic device in order to image closer to the device level of electronic device.

Another optical technique for surface temperature measurement was proposed by Grimes and Davies [33] in 2004. The IR camera field of view was arranged such that the temperature across the surface of the entire PCB was captured. The material in the system wall between the IR camera and the PCB had to be transmissive for the surface temperature to be measured. A polypropylene film, calibrated against a thermocouple, met this requirement. Figure (4.9) shows a schematic of the experimental set-up. From this schematic, radiative heat can be seen to reach the IR camera from three separate sources.

Figure 4.9: Schematic of IR thermography measurement of Component surface temperature through a polypropylene film [33].

(1) Q_s is the heat radiated by the PCB surface. Q_t is the fraction of Q_s that reaches the camera.

$$Q_t = \tau_f Q_s = \tau_f \sigma \epsilon_s T_s^4 \quad (4.15)$$

Where σ is the Stefan–Boltzmann constant, ϵ_s is the PCB surface emissivity, τ_f is the transmissivity of the polypropylene film and T_s is the PCB surface temperature.

(2) Q_{ra} is the quantity of heat radiated by the polypropylene film that reaches the camera:

$$Q_{ra} = \sigma \epsilon_f T_f^4 \quad (4.16)$$

Where ϵ_f is the polypropylene film surface emissivity and T_f is the polypropylene film surface temperature.

(3) Q' is the amount of heat radiated by background surfaces. Q_{re} is the quantity of that heat which is reflected off the surface of the polypropylene film to the IR camera:

$$Q_{re} = \rho_f \sigma \epsilon' T_\infty^4 \quad (4.17)$$

Where ϵ' is the background surface emissivity, ρ_f is the polypropylene surface reflectivity and T is the background surface temperature. The total heat radiated to the IR camera is therefore

$$Q_T = \sigma \epsilon_s \tau_f T^4 + \sigma \epsilon_f T_f^4 + \sigma \epsilon' \rho_f T_\infty^4 \quad (4.18)$$

Where T_{ap} is the PCB surface temperature, which is apparent to the IR camera as a result of the radiation Q_T that reaches it.

This is the uncalibrated temperature, which the IR camera reads. Assuming $T_f \approx T_\infty$ and rearranging equation (4.19) gives

$$T_{ap}^4 = ((\epsilon' \rho_f + \epsilon_f) / \epsilon_s) T_\infty^4 + \tau_f T_s^4 \quad (4.19)$$

Calibration was performed by measuring values of T_s with a thermocouple over a range of values of T_{ap} . To ensure the radiative properties of the polypropylene film did not change with time (due to possible contamination of its surface), calibration was performed before and after the measurement cycle, and to ensure consistency of these properties between locations, calibration was carried out at different points on the PCB surface.

J. Renau and Michael Brown suggested different setup for thermal mapping of microprocessor on the basis of oil-based heatsink in 2007 [26]. The proposed setup measures processor temperature using an infrared camera. First, the proposed measuring setup captures the chip temperature with an infrared (IR) camera. An infrared transparent heatsink is used to allow the IR camera to obtain the processor die temperature. This transparent heatsink is capable of dissipating up to 100W, thus it is aptly suited for most modern high performance processors. Figure (4.10) shows the measurement setup.

Figure 4.10: Measurement Setup [26].

The IR camera frame rate (125fps) can be increased up to 10 KHz as long as the bandwidth of the camera stays under 1GB/s. E.g.: If the measurement experiments require it, it is possible to capture 1000 thermal frames per second (1 KHz) with a $100 \times 80 \mu m$ resolution. Second, the data must be processed to remove distortion.

To keep the processor in operational conditions, an IR transparent heatsink must be implemented and a mineral oil (Fluka Mineral Oil 69808) flow on top of the silicon substrate is created. Even though water has around 2.5 times the specific heat of mineral oil, one cannot use it because it is not transparent to the infrared spectrum. Several oils like olive oil are partially transparent on the infrared wavelengths. Mineral oil is designed

for infrared spectrography and delivers excellent infrared pictures. 1⁰C oil temperature increase from side to side of the chip. The setup is capable of dissipating up to a 100W. 2 liters oil is put in the oil reservoir and is connected to a small radiator to guarantee minimal temperature oscillations during each run.

4.5 Summary

The principle of Infrared thermography and fundamentals of operation of infrared camera are explained in detail. The concept of blackbody radiation and various scientific laws pertaining to radiations are also discussed. The method by which Infrared camera reads the temperature from the surface of an electronic device is also explored. The advantages of the development of heatsink in infrared thermography are discussed.

Several infrared thermography methodologies and setups on Printed Circuit Boards, Integrated circuits and other electronic devices were introduced. The reasons for the implemented setup have been mentioned for each case.

Chapter 5

Test Equipment and Instrumentation

A variety of equipment was required to conduct the experimental tests, depending on the purpose of the test. The amount and type of equipment and the scope of the test itself depends on the type of the test and the desired results. The total number of external rings required for focus depends on distance of object from camera lens. High speed data recorder is required in order to perform high speed transient analysis (above 125 frames per second). The scope of the setup can be expanded if the electronic device under test is critical and requires high speed analysis. In this chapter, the major equipments that are used in experiments are introduced. The apparatus used in the experiment include optical measurement system, which are a FLIR infrared camera system, thermocouple, digital thermometer, Instrumentation Project Hardware Board (68HC11 Microcontroller Board), LCD, Boron Nitride Spray, Black Spray Paint, infrared transparent oil (Aldrich oil), Oil Pump and power supply. A typical test set of optical system is shown in figure (5.1). The equipment and instrumentation used to conduct the test are listed in this chapter.

Figure 5.1: Typical Experimental setup.

5.1 Infrared camera system

The infrared camera system used in the experiments is FLIR SC 4000 system. This system has been recently installed at Electro-thermal Laboratory of Electrical and Computer Engineering Department of Ryerson University. This infrared camera system has high spatial resolution ($10 \times 10 \mu\text{m}$) and high frame rate (125Hz) to capture thermal maps. The setup is capable of capturing up to *125 frames per second (fps)* with a $320 \times 256 \text{ pixels}$ resolution with a sensitivity of 25mK per pixel, and it can be applied to multiple chips with relative simplicity. The IR camera system frame rate (125fps) can be increased up to 10 KHz as long as the bandwidth of the camera system stays under 1GB/s. e.g. If the experiment requires, it is possible to capture *1000* thermal frames per second (1 KHz) with a $100 \times 80 \mu\text{m}$ resolution. Figure (5.2) shows the FLIR SC 4000 infrared camera system used in the present work.

Figure 5.2: FLIR SC 4000 IR Camera system [26].

The IR camera system has simultaneous and independent analog and digital output data streams. An example of this capability would be sending corrected imagery to a video monitor while different data is being sent to a digital recording system. This capability also works in windowing mode maintaining the analog video output. It means that video signal (captured during recording) is sent to any other video monitor (Television, Desktop) and temperature values are fed to a digital recording system. IR camera system supports up to four active presets, or operating modes, with adjustable integration times, embedded non-uniformity correction and bad pixel replacement. The presets can be used individually or in a continuous cyclic mode for preset sequencing and super framing. To

generate an accurate thermal map for a given chip, the temperature at multiple points needs to be measured. Therefore, an IR camera system can be used to measure temperature as close as possible to the transistor junction.

Using the PC-Link (Gigabit Ethernet), the camera system is designed to capture and transfer 125fps with 320×256 spatial resolutions. This camera system operates on the 3-5 μ m wavelength (MWIR) a range of light where silicon is transparent. As a result, the IR camera system is capable of measuring the temperature “through” the chip being tested. Indium Antimonide (InSb) sensors available on IR camera system, have a high sensitivity per pixel (25 mK). This corresponds to the IR camera system’s optimal accuracy once it is correctly calibrated. The specification of the SC4000 IR camera System can be found in Appendix 1.

5.2 Data Acquisition System

The data was captured and analyzed using integrated data acquisition system of optical system, supported by PC-based ThermoCAM Researcher software for data acquisition, analysis and reporting. The acquired input data were recorded in real time for subsequent analysis using this software package. Additionally the IR camera system system has an optional Software Developers Kit (SDK) for custom programming.

5.3 Thermocouple

Thermocouple is used to measure temperature on the surface of the printed circuit board in this experiment. A thermoelectric device used to measure temperatures accurately, especially one consisting of two dissimilar metals joined so that a potential difference generated between the points of contact is a measure of the temperature difference between the points. There are several types of thermocouples available. They are usually selected based on the temperature range and sensitivity needed. Other selection criteria include the inertness of the thermocouple material, and whether or not it is magnetic. The thermocouple types are listed below with the positive electrode first, followed by the negative electrode.

Thermocouple used in the experimental efforts is the K-type. Type K (chromel–alumel) is the most commonly used general purpose thermocouple. It is inexpensive and, owing to its popularity, available in a wide variety of probes. They are available in the $-200\text{ }^{\circ}\text{C}$ to $+1350\text{ }^{\circ}\text{C}$ range. The type K was specified at a time when metallurgy was less advanced than it is today and, consequently, characteristics vary considerably between examples. Another potential problem arises in some situations since one of the constituent metals, nickel, is magnetic. The characteristic of the thermocouple undergoes a step change when a magnetic material reaches its Curie point. This occurs for this thermocouple at 354°C . Sensitivity is approximately $41\text{ }\mu\text{V}/^{\circ}\text{C}$ which is a very good sensitivity.

5.4 Digital Thermometer

Digital Thermometer is used with thermocouple probe to record and display the temperature of electronic devices. The digital thermometer used in the present work is HH-23A from Omega Industries. The HH-23A accepts dual inputs. HH-23A works with J, K or T types. It can display T1 (input 1), T2 (input 2), T1-T2 (difference), or scan between T1, T2 and T1-T2. Standard features include display hold, min and max storage and trend indication. The min and max functions record minimum and maximum values for T1, T2 and T1-T2. Trend output shows if the displayed is increasing or decreasing. Figure (5.3) shows the image of digital thermometer. The specification of the Digital Thermometer HH-23A can be found in Appendix 2.

Figure 5.3: Digital Thermometer.

5.5 IPB V1.0 Hardware Board (68HC11 Microcontroller Board)

IPB V1.0 Hardware Board is shown in figure (5.4). The features of this board are as follows:

- Processor Motorola MC68HC11E1CFN2
- 52 pin PLCC package
- 8 Channel, 8 bit resolution A/D
- Serial Communications Interface
- Serial Peripheral Interface
- 5 output timer channels, 3 input timer channels
- 512 bytes EEPROM
- 512 bytes RAM

This board supports one 28 pin EPROM of sizes 8K (2764), 16K (27128) or 32K (27256) or 32K (27256), selected by means of jumpers on pins 26 and 27 of the socket. Thus the starting address of an EPROM depends on its size. It also supports one 28 pin RAM, sizes 8K and 32K, by means of jumpers on pins 1 and 26. One eight bit parallel input register, device 74HC244 or equivalent is mapped into the memory address space. Eight bit parallel latch, device 74HC273 or equivalent has been mapped into the memory address space. The input and output lines are connected to header. A header is supplied to

for attachment of LCD display. The LCD display has been mapped into the memory space of the microprocessor. The memory map is decoded by a 16V8 Generic Array Logic (GAL) device, which must be programmed with memory map. Outputs of the decoder select the EPROM, RAM, Input Register, Output Register and LCD display header.

The GAL supplied with the kit is programmed with the memory map equations. Hence the GAL IC forms the important device on the board to determine the temperature of it. Either 4MHZ or 8MHZ crystal may be used but LCD works with 4MHZ crystal only. Unless you have good reason to use an 8MHZ crystal, 4MHZ is advised. A momentary action pushbutton is present on the board for reset. PCB mount DB-9 connector on the board is configured for a direct serial (COM) port connection to a PC. The raw 9 volts is brought to a pad or terminal to support the powering of single supply op amps from a supply greater than +5 volts. Bipolar power of +/-10 volts and a few milliamps is available from the RS232 level converter. This might be useful to power one or two op amps or other low current devices that require bipolar power.

A Maxim MAX232 or Linear Technology LT1081 translates the 5 volt logic signals to and from the RS-232 logic swing and helps isolate the microprocessor board from the P/C development system. The SPI is one of several ways to connect external devices to the microprocessor, either to sense external signals or generate signals to control other devices. The following pins are pulled up by resistors to +5 volts: XIRQ, IRQ, MODA, MODB, IC1, IC2, and IC3. Each pin has an associated wire. In order to support single stepping operation using the Buffalo monitor, OC5 must be connected to XIRQ. Two adjacent header pins are provided for this purpose: jumpering them connects OC5 to XIRQ.

Three LEDs are provided to indicate the board status and help diagnose problems: Power, Serial port transmit, and Serial port receive. The board includes a 5 volt regulator with room for a small heatsink if required. The unregulated power input connection is via a power coaxial jack which mates with a 9 volt, 500 mA DC adaptor wall wart power supply. The unregulated power input connection includes a power diode to prevent the

reverse application of power. Unused board area is given to a matrix of holes on 0.1 inch centers for application-specific circuitry. So the hot spot is expected to appear near the heatsink and 16V8 GAL IC as heat is going to be completely dumped at the heatsink and GAL IC is memory decoder IC which comes into place even if only LCD is the peripheral device to be connected. The schematic of the circuit under test is given in the figure (5.4).

5.6 Boron Nitride Spray and Black Spray Paint

Rescor 112 Boron Nitride Spray is used as one of the coating so as to have uniform emissivity for the experimental setup. Boron Nitride has an excellent electrical insulation, high thermal conductivity and is a superior high temperature lubricant. It is inert to most molten metals, glasses and salts. This unique combination makes for an ideal high temperature lubricant, mold release and electrically resistant coating. Use continuously to 1500°F in air and to 3600°F in inert atmospheres.

This unique combination makes for an ideal high temperature lubricant, mold release and electrically resistant coating. Black Spray paint from Aervoe industries is used for having the uniform emissivity on PCB. It is non-freezing and operational up to 1400F. It provides best quality paint in terms of retention and durability, which is very important from the experimental point of view, and moreover it adheres to any surface.

of mineral oil, we cannot use it because it is not transparent to infrared wavelengths. Aldrich oil is designed for infrared spectrography and delivers excellent infrared pictures. The chosen oil setup is selected as a balance between ease of modeling and accuracy. Turbulent oil flow can remove more heat than laminar flow, but it is significantly more difficult to model accurately. Previously, Fluka Mineral (69808) oil was used for the same purpose. Aldrich mineral oil has lower density than Fluka oil, i.e. 0.838 g/mL at 25⁰C (Lit). But both are designed for IR spectroscopy.

5.8 Oil Pump

Figure 5.5: Shurfflo Utility Pump.

The utility pump shown in the figure (5.5) is suitable for variety of tasks such as pumping fluid to oil transfer. It is designed specially for harsh fluid transfer; the utility pumps come with heavy duty valves and diaphragm to handle the harshest liquids. A 12VDC battery has been used as the input source. The specification of the oil pump can be found in Appendix 3.

5.9 Summary

The major equipment and the systems used in the optical measurement experiment have been discussed in detail in this chapter. The new optical FLIR SC 4000 system, which has been recently installed at Electro-thermal Laboratory of Electrical and Computer Engineering Department of Ryerson University, has been described. This system has high

spatial resolution ($10 \times 10 \mu\text{m}$), high frame rate (125Hz) to capture thermal maps, a 320×256 pixels resolution with a precision of 25mK error per pixel. Paints are used to have same emissivity throughout the electronic device. Infrared transparent heatsink comprising of IR transparent oil is used to keep temperature rise within the desired range. The detailed explanation on the need of infrared transparent heatsink is given in the previous chapter. Thermocouples and digital thermometer are used for initial validation of the infrared camera system results. In addition, they are applied for continuous monitoring of infrared transparent (Aldrich) oil temperature during the experiment. The complete implemented setup and optical system validation is described in detail in the next chapter.

Chapter 6

Experimental Test Setup

In this chapter we will elaborate our method to develop new experimental setup for infrared thermography of electronic devices. This setup takes into account the leakage power of electronic components on PCB. Spatial resolution of images and a realistic cooling approach is suggested. The methodology of cooling PCBs and ICs for infrared thermography, the implemented setup and its validation will be reviewed.

6.1 Experimental Setup

An experimental setup should be designed in such a way that it plays a vital role in the testing phase of manufacturing of electronic devices. It should be able to generate an accurate thermal map and should be able to take into consideration all the external as well as internal parameters influencing the performance of electronic devices. External parameters include humidity, atmospheric temperature, distance of measurement, reflected temperature, emissivity and radiations from other objects. Internal parameters include heat spreading, leakage power of electronic components, fault detection, fault location and cooling of electronic device. To generate an accurate thermal map for a given chip, temperature should be measured at different locations. Therefore, optical camera system should be placed as near as possible to device under test (DUT). The care should be taken that distance of measurement does not exceed rated minimum distance of measurement, which is 15 centimeters in our setup. The emissivity of the surface under the measurement should be uniform. As mentioned in the previous chapters, efficient cooling of electronic circuits is also necessary to compute the surface temperature of the DUT.

To overcome the obstacle of having uniform emissivity, a comparison is made between applying the uniform coating of high-temperature black spray paint and a uniform coating of boron-nitride spray to the DUT. Both coating materials came in typical aerosol spray to the DUT. Using the black spray paint to provide a uniform surface emissivity is a common technique and has the advantage of mimicking an ideal black body surface with the drawback of being a more permanent coating that would be difficult to remove. The

Boron Nitride coating is selected based on its thermal conductivity and ease of removal from surfaces. This coating washes off using isopropyl alcohol. The impact of these coatings on the camera system, initial tests performed by Salem [29] can be considered as a benchmark. The IPB V1.0 board painted with boron nitride spray is shown in the figure (6.1).

Figure 6.1: IPB V1.0 board painted with Boron Nitride Spray.

Moreover the image obtained by the optical camera system on the computer is shown in the figure (6.2).

Figure 6.2: Camera system Image on Computer.

Although the technique of inserting a black body as a temperature reference in the test could have been done, using a thermocouple is preferred since it provides common temperature reference for all the tests. Here also, the temperature measured by IR camera system is compared to the ones obtained by K- type thermocouple. By adjusting emissivity values for different layers of coating, error minimization was achieved. Figure (6.3) shows the typical experimental setup to have the uniform emissivity.

Figure 6.3: Experimental Setup for having uniform emissivity.

The second important factor to be considered for the measurement is cooling of the integrated circuits. Oil based heatsink is preferred, because of its efficiency of cooling, in this work compared to all the other heatsink arrangements proposed in [33]. The transparent heatsink is capable of dissipating up to 100W. The setup is capable of capturing up to 125fps with a $10 \times 10 \mu\text{m}$ spatial resolution, and it can be applied to multiple chips with relative simplicity. Aldrich Oil (161403 Mineral Oil for IR Spectroscopy), which is infrared transparent, was used for creating an oil flow over the 68HC11 microcontroller board in this work. Two (2) liters of oil is kept in the bucket, which can be called as reservoir. Moreover, the comparison is being made with temperature readings obtained by thermocouple. Figure (6.4) shows the setup with oil

based heatsink. The results obtained with this setup demonstrate that heat spread that has taken place due to the leakage power is being considered.

Figure 6.4: Experimental setup with Oil based heatsink.

As shown in the figure (6.4), PCB is kept at bit higher level than the oil. The oil is pumped with the oil pump, which is operated by 12VDC battery, and thereby oil flow is created on PCB (kept in operating condition). An IR camera system, which is mounted on tripod, is connected to the computer gigabyte Ethernet port.

6.2 Procedure of the Experiment

First of all, to demonstrate usage of thermal mapping some preliminary steps were conducted. A general steady state image of real time operating microcontroller board is taken to determine the hot spots and temperatures at various other locations of the 68HC11 microcontroller PCB. Therefore, infrared camera system is mounted on the tripod as shown in figure (6.3 & 6.4). The camera system is connected to the computer with gigabit Ethernet port of the system as well as computer. Power supply is drawn to the circuit board. The total power supplied to the PCB is 2.7 watts, which is drawn by 9 volts DC adapter. To increase the accuracy of the image, object parameters such as emissivity, humidity, reflectivity, atmospheric temperature and distance of measurement are to be set as feasible as to the surrounding location. For example, atmospheric

temperature should be set after measuring it with thermocouple and digital thermometer. The room temperature humidity is taken as 50%. Distance of measurement should be measured with proper measuring equipment. This parameter influences on the readings by substantial amount, so it should be set measured accurately and fed in the image parameter settings of the camera. Discrete location is preferred to minimize reflection. In order to keep the microcontroller in service, the circuit board is programmed to display a message on the screen. As the optical system works with the Windows operating system, MiniIDE is the editor used to program the board in the assembly language. For e.g., the program loaded in the microcontroller is to display the message "HELLO WORLD". The software code for it is presented in appendix 4. Apart from this, the circuit is also programmed to convert analog signal to digital signal i.e. A/D Converter. This program can read an analog quantity (such as the power supply voltage) and display it on the LCD. This includes the following steps:

- Read the A/D Converter
- Do a fixed point calculation, including scaling
- Display a binary number on the LCD using binary-BCD and BCD-ASCII conversion routines.

A potentiometer (the *frob knob*) that can be adjusted is used to generate a variable voltage. The A/D converter of the 68HC11 reads voltages between zero and 5 volts, and generates a binary number proportional to the input voltage. Potentiometer is put on A/D channel 1 to its minimum setting and the A/D should read close to zero. Pot is put to its maximum setting and the A/D should read FF (or close to it). Pot is put about mid-point, and the A/D should read something about halfway between 00 and FF. (Ideally, 7F). The software code for it is presented in appendix 4.

In order to investigate the transient response of the circuit, the images are recorded with the ThermaCAM Researcher software for both the cases. The transient response i.e. variation of temperature with time for the various locations has been plotted and time required to reach the steady state is also recorded. Moreover a deliberate short circuit fault was created at two terminals of the capacitor C_{16} . Due to creation of short circuit fault, the hot spot changed its location completely. Along with this, if histogram is

required in a particular region as well as average temperature across a line can also be investigated with the software tools.

In the second part of the experiment, the accuracy of thermal map produced is to be estimated. The 68HC11 microcontroller circuit board is painted with boron nitride spray paint. Once the steady state is reached, the camera system is focused by rotating the lens and temperature readings are taken at the several locations. The temperature readings are also taken at the same spot by the K-thermocouple probe and digital thermometer (HH23A). The probe can be clamped at particular spot and its location can be seen on computer screen through camera system. The readings are compared and the corresponding percentage errors are also calculated which will be notified in the chapter 7. Several different combinations of the boron nitride and black paint coating are experimented to reduce the percentage error. The combination of number of layers of coating and emissivity values that gives the minimum error and their comparisons with the available results are explained in the chapter 7. The emissivity is the main part in this section of experiment. Emissivity is put manually in the object parameters setting of the image varying from 0.88 to 1 in the increment of 0.02. The value of emissivity is taken with reference to the ones provided in the literature and a slight deviation from it. As the number of layers of boron nitride or black color paint used increases; the value of emissivity approaches to 1. The thermocouple readings are taken only after thermocouple is clamped at the particular location for 2 minutes of time. Moreover there is indication on the digital thermometer (HH 23A) when the readings are stable and when they are increasing or decreasing. Hence we can rely only on thermocouple readings for the validation of IR camera system results as it is in physical contact of the spot where the temperature is measured.

Finally in third stage of experiment, circuit board or PCB is held on stand in the bucket to some height. The 161403 Aldrich mineral oil is filled in the bucket but it is at the lower level than the PCB. The oil is designed for IR spectroscopy. The oil is taken from the bucket through the pipe and then pumped on the upper layer of the PCB to create laminar flow. Actually turbulent flow is better for heat removal efficiency; however it is very difficult to set it up. The turbulent flow cause the temperature on the specific spot or over the given device keeps fluctuating over a large range. The similar steps regarding

camera system and the circuit board connection are to be followed that were applied in first stage for the procurement of camera image successfully. The oil temperature is continuously monitored by digital thermometer. The camera system readings are compared with those obtained with thermocouple and the corresponding percentage errors are calculated and are presented in chapter 7. The pump is running with 12V DC car battery. All the other steps of the experiment for the operation of camera system and its connection of the computer will remain same as the ones that were followed in the first two stages of the experiment.

Apart from emissivity and cooling rate, there are other factors such as reflectivity, atmospheric temperature, distance of measurement (distance between camera system lens and the surface on which temperature is to be measured), humidity, and reflectance from surrounding objects that affect the measurements. Hence isolated work place is preferred for setting up the experiment. Atmospheric temperature measured by thermocouple and digital thermometer is placed in object parameters of image.

The humidity at the instant of experiment is observed online. As there is large amount of variation in humidity of outside environment and inside environment, humidity is taken on an average of 50%. Again variations in humidity value are done accordingly during the time of experiments if there is wide fluctuation in humidity value, which is observed online. All these parameters are to be set every time camera system is operated from the very beginning; moreover there is possibility that there might be rise in atmospheric temperature, so an updated temperature must be fed in the object parameter setting of image to keep the track of the atmosphere. Thus the temperature readings obtained from IR camera system are correct and stable.

6.3 Challenges and Issues Incurred

There were many issues faced during the execution of experiments. First of them was to figure out all the equipments that are required for an accurate experimental set up. There are several accessories available in the market, but to get the right test setup to achieve an accurate measurement is the state of art. The infrared camera system used in this research project is one of the best available IR systems, which is having an accuracy of $25mK$ per pixel. The spray paints used in the experiment are among the best ones that can be

proposed for IR thermography. The paint should have the properties such that it does not decay and that it can be painted on the chip homogeneously. The paints should be removable after performing experiments. The thermocouple used for verification is having an accuracy of $41 \mu\text{V}/^\circ\text{C}$. The oil used is having density of 0.838 g/mL , which is designed for IR spectroscopy and is having the lowest density. Several other toxic fluoride materials are extremely transparent to IR with a high capacity to cool down electronic devices. But, to avoid dangerous lab materials safer products are preferred. Hence the best test equipments have been considered by the complete study of properties of available options. The factors such as reflectivity, atmospheric temperature, distance of measurement (distance between camera system lens and the surface on which temperature is to be measured), humidity, and reflectance from surrounding objects are critical for the stability and consistency of results. All transparent and translucent materials should be avoided during the setup, as they tend to give reflections. Any moving objects should be avoided from the field of view of system setup. The reflections from the moving bodies completely change the image obtained and therefore isolated workplace is preferred. The distance of the measurement between the camera lens and device under test is critical. It was measured with the measuring tape. The atmospheric temperature was measured by thermocouple probe. There is another parameter called reflected temperature, which needs to be entered in the IR camera system. This value should be set to the current atmospheric temperature if system is set in the isolated workplace. In case there is no isolated workplace, there will be significant fluctuations in the results and will give rise to inconsistency. The value of emissivity is 0.92, which is the default value present in the system. It needs to be changed for the experiments. Apart from emissivity tables, as explained in the previous section as the number of layers of coating on the device under test increases, the emissivity value increases. The complete results and their validations for different layers of coatings of spray paints are discussed in chapter 7.

For the external optics section of image settings, parameters such as temperature, transmissions are to be determined. These parameters refer to the far end transmissions and temperatures of the system surroundings. The atmospheric temperature measured by thermocouple and digital thermometer was considered for external optics temperature.

The transmission parameter varies between 0 to 1 and its value is 1 if there are no obstacles at the distance of 100 to 200 meters. But, the infrared camera system itself calculates the transmission that is called computed transmission. If the value of computed transmission is less than 1, the value of computed transmission should be used in external optics section. Thus, all the above mentioned parameters need to be set as mentioned in the above manner.

The setup of the experiment should be capable of providing real time temperature values accurately. The major challenge in using Infrared camera system was to develop IR-transparent heatsink. For the removal of heat spreading between electronic devices on printed circuit boards, Infrared transparent heatsinks need to be designed. Infrared transparent heatsinks cannot be designed with aluminum heatsinks available in the market. The prominent issue was the complicated turbulent flow associated and more importantly, the low capacity to remove heat and associated slow thermal response. The oil flow created in infrared transparent heatsinks needs to be uniform, which is very challenging to achieve. Proper suction and discharge is required from the oil pump to achieve the uniform oil flow. The oil available in the bucket is 2 liters, hence suction pipe should be properly dipped in the oil and it should not touch the bottom level of the bucket. The discharge pipe needs to be held at 45° with respect to the device under test in order to create uniform laminar flow. The oil should flow over the complete printed circuit board and should be continuous.

The reviewed available literature indicated the necessity of having the oil flow setup with development of infrared transparent duct over the DUT [32]. But due to development of infrared transparent heatsink, the thickness of oil flow over the device increases and even though it is infrared transparent, oil generates signals that can be captured by camera system which may affect the results. Therefore, oil flow was created without any duct over the device and the thickness of oil was kept to 2mm in order have accurate thermal measurements.

Since the experiments are performed on real time operations of electronic devices, connections of wires to the electronic devices should be protected at the junctions of wires and devices. Hence oil proof adhesives can be used to prevent the entry of oil in the various sensitive ports of the electronic devices. In this project, oil proof tapes were used

at the junctions of RS232 cable connection port and power supply port. All these factors play an important role to maximize the accuracy of results.

6.4 Summary

In this chapter, the methodology and implementation of experimental set for thermal mapping has been reviewed. By making use of various paints for uniform emissivity, as well as oil based heatsink, this technique can be practiced in the electronic industry at testing and verification stage. Various factors affecting temperature measurement were elaborated in this chapter, and the complete procedure of experiment test was also described in details. The most important challenges and issues incurred during the performance of experiment have been discussed.

Chapter 7

Thermal Mapping on IPB V1.0 Board

To investigate the performance of the new experimental approach towards thermal mapping, several experimental methods have been proposed and have been practiced. Steady state and transient analysis were performed on the 68HC11 microcontroller board. The effect of two different coatings, number of coating layers, emissivity and oil based heatsink within several test setups have been investigated. There have been wide changes being made in the experimental setup to achieve the accuracy. The obtained results are very encouraging. The following sections are elaborations of these experimental analyses.

7.1 68HC11 Microcontroller Printed Circuit Board

The proposed optical thermal mapping methodology was applied to study the temperature gradient on a 68HC11 microcontroller printed circuit board. The hot spot or the maximum temperature was expected at the heatsink on the circuit board and the Generic Array Logic (GAL) decoding IC. This IC was programmed with memory map equations during the experimental efforts. No other serial output port is used.

7.1.1 Steady State Analysis

In the steady state analysis, Power was injected in PCB and PCB was programmed to display any message on the screen. MiniIDE is the editor used to write an assembly level language program. When the circuit reached the steady state the measurements were taken. The question was how to figure out whether PCB has reached the steady state or not. A time interval of five to six minutes was given after the power was applied to PCB circuit to reach the steady state as it operated at low frequency. This value of time is taken from PCB description and was verified experimentally also. Moreover, we were also able to figure out in the manner if there was no increase in temperature at several locations of the image obtained by the optical thermal mapping system. The

typical steady state captured temperature profile of the 68HC11 controller board is shown in the figure (7.1).

Figure 7.1: Steady state captured temperature profile of the 68HC11 Microcontroller Board.

It can be observed that the hot spot is located at the centre of the GAL IC which is used for memory mapping. Apart from that, higher temperature is also located near the heatsink region as most of the heat is dissipated. The maximum temperature obtained at the hot spot was 35°C. Figure (7.2) is the captured temperature profile of the 68HC11

Figure 7.2: Steady State captured temperature profile with two terminals of Capacitor C₁₆ shorted.

microcontroller board with one of the capacitor shorted on the board. The capacitor near the GAL decoding IC, C_{16} was shorted. So there was significant observable change in the location of the hot spot. By comparing the figures (7.1) and (7.2), the location of the hot spot was completely changed. Hence if we just have general information regarding the temperature distribution to be obtained through experiments, we can easily detect fault in the vicinity of changed location of the hot spot. Moreover, it is visible that there is change in temperature of the heatsink and the centre spot of Generic Array Logic IC; this is because the thermal mapping in the figure (7.1) was taken only after 4 minutes of powering up the circuit. Hence, it is required to give complete time to the board before taking any state readings. There is minor difference in the value of maximum temperature shown in figure (7.1) and its scale, it is on account of setting in camera.

7.1.2 Transient Analysis

Transient analyses were performed on the 68HC11 microcontroller board. The temperature of expected hot spot, heatsink and GAL IC was recorded right from the beginning of the powering of the circuit. GAL IC is the memory decoding IC, so any program fed in the microcontroller, for the decoding process this IC always plays its part in the proper functioning of the microcontroller board. Hence it becomes vital to examine the temperature of the GAL IC during real time operation. Along with the graphical representation of the temperature rise, thermal mapping were also recorded on a constant time increment.

Figure (7.3) presents temperature evolution of the hot spot, heatsink and the spot 3, which was the hot spot when the terminals of capacitor C_{16} were not shorted. Capacitor C_{16} was chosen as a mere example to represent the fault testing by infrared thermography and because some activity with its terminals creates change in the operation of one of the device on the printed circuit board i.e. GAL IC in this case. It can be seen that the temperature of the heatsink, spot 3 and hot spot increase from 25°C to 33.1°C , 35.3°C and 38.4°C , respectively. Figure (7.4) shows the thermal mapping of PCB under the condition where C_{16} was shorted. Therefore, there was dramatic change

in the location of the hot spot. The temperature profiles for this condition are shown in the figure (7.4a-d).

Figure 7.3: Transient Temperature rise of Heatsink (blue line) and Spot 3 (green line) and Hot Spot (red line).

(a)

(b)

(c)

(d)

Figure 7.4: Power ON: Temperature profile at (a) $t=0$ sec (b) $t=60$ sec (c) $t=3$ minutes (d) $t=6.5$ minutes.

Note that in the temperature profile shown above, the two terminals of capacitor were shorted, that is the reason why we don't have the hot spot near GAL IC. Similarly for the switch OFF condition, the transient temperature profiles are shown in the figure (7.5a-d).

(a)

(b)

(c)

(d)

Figure 7.5: Power OFF: Temperature profile at (a) $t=0$ sec (b) $t=60$ sec (c) $t=3$ minutes (d) $t=6.17$ minutes.

The steady state was reached faster in the power OFF stage rather than in the power ON stage. These thermal mapping were taken before programming of the microcontroller. Similar thermal mapping were taken after programming the microcontroller. There is not much difference in the obtained results but it was necessary to investigate temperature distribution when it is actually in operating condition. We have concentrated only on the power off condition after programming of the board. For either transient or steady state analysis, one can get the histogram of temperature across the line or any region. Moreover temperature variation across any given line can be obtained. Figure (7.6) is the example of the line, where image (a) represents the histogram which shows the variation of temperature value in its class limits and image (b) represents the variation of temperature along the line. The line here is the one that is drawn along the side of the (GAL) IC.

(a) Histogram across a line.

(b) Variation of Temperature across line along the GAL IC.

(c) Line along GAL IC

Figure 7.6: Temperature Profile of line.

Figure (7.7) shows the IR captured temperature profile of the board when the power was disconnected after programming the board by displaying “HELLO WORLD”. The temperature profile from (7.7a-d) represents the several transition stages of microcontroller board when the board was turned off from the supply.

Figure 7.7: Power OFF; Temperature profile after Programming at (a) $t=0$ sec (b) $t=60$ sec (c) $t=3$ minutes (d) $t=4.20$ minutes.

Figure (7.5) and (7.7) are quite similar. There is not much difference between figure (7.5) and (7.7), however, the maximum temperature reached in figure (7.5a) was 0.4°C higher than the one obtained in the figure (7.7). Apart from that, the rate at which temperature decreases after programming was quite fast as compared to the previous case.

Moreover, maximum temperature recorded in the figure (7.7d) was quite higher compared to the one obtained in the figure (7.5d). This higher temperature has been recorded for a period of time, so it was not reduced to the minimum atmospheric

temperature and some residual temperature remains in the board. Figure (7.8) shows the transient temperature decrease when the circuit was disconnected from the power supply.

It can be seen that the temperature of the heatsink, spot 3 and hot spot decrease from 33.1°C, 35.3°C and 39°C, to 25.6°C, 25.7°C and 27.3°C, respectively after 4.2 minutes.

Figure 7.8: Transient temperature decrease of Heatsink (blue line), Hot Spot (red line) and Spot 3 GAL IC (green line).

Figure (7.9) shows the IR captured temperature profile of portion of the heatsink portion of board, when the power was disconnected after programming the board as A/D converter. The temperature profile from (7.9a-d) represents the several transition stages of microcontroller board when the board was turned off from the supply. There is gradual decrease in the temperature as power supply disconnected from the circuit as there is decrement in the generation of heat.

Figure 7.9: Power OFF; Temperature profile after Programming at (a) $t=0$ sec (b) $t=60$ sec (c) $t=3$ minutes (d) $t=4.20$ minutes.

The rate at which temperature decreases after programming was quite fast as compared to the previous case. In figure (7.9d), the temperature does not fall down to atmospheric temperature, which is 21.6°C . And this higher temperature has been recorded for a period of time, so it was not reduced to the minimum atmospheric temperature and some residual temperature remains on the board, this due to the residual energy stored in the stray capacitances of the circuit board.

Figure (7.10) shows the transient temperature decrease when the circuit was disconnected from the power supply. It can be seen that the temperature of the heatsink, and hot spot decrease from 28°C and 30°C to 23°C and 23.1°C , respectively after 4.2 minutes.

Figure 7.10: Transient temperatures decrease of Hotspot (green line), Heatsink (pink line).

7.2 Emissivity Effect

The results obtained in the previous section were improved to include the emissivity effect on the optical temperature measurement system. As discussed in the previous chapters, this system requires a uniform surface emissivity coefficient in calculating the temperature, which is often not found due to variety of surfaces and materials in a packaged electronic system. Hence Boron nitride spray and black color spray were used to paint the PCB to achieve the uniform emissivity. A typical steady state IR temperature profile of heatsink and hot spot with a single layer of Boron Nitride Spray uniformly painted on it is shown in the figure (7.11a-b).

Figure 7.11a: Obtained temperature profile w/o any coating.

(i) Heatsink.

(ii) Hot Spot.

Figure 7.11b: Obtained temperature profile with Boron Nitride coating.

It is concluded that the difference in clarity, accuracy and quality of temperature distribution between figure (7.11a) and (7.11b). The results obtained by IR camera system were compared to the ones obtained from the k-type thermocouple probe and digital thermometer. The presence of inaccuracy in the obtained temperature profile without any coating was represented in the figure (7.12). The reference temperature is taken as atmospheric temperature that was measured with thermocouple and digital thermometer. Figure (7.12) shows the error percentage in temperature measurement obtained from infrared system compared with thermocouple temperature readings. Maximum 10% error is observed. This leads us to study the effect of coating material, number of applied layers and emissivity setting of the infrared system on the thermal mapping results.

Figure 7.12: % Error in the obtained temperature profile (without any coating) compared to thermocouple results.

Figure (7.13) shows the comparison of percentage errors obtained between 3 layers of Boron Nitride and 5 layers of Black paint spray. Moreover there was visibility kept in mind to compare the errors at different temperature locations. However, there was no specific trend to be found in the percentage error with respect to the locations. In this scenario, black paint performed better than the Boron nitride spray.

Figure 7.13: % Error Comparison.

The percentage error comparison for 3 layers of Boron Nitride spray with emissivity=0.94 and 5 layers of black spray paint with emissivity=1.00 is shown in figure (7.14).

Figure 7.14: % Error Comparison.

The value of emissivity was kept lower for Boron Nitride spray compared to black paint spray in figures (7.13) and (7.14). This is the major reason for which black spray paint performs better than boron nitride spray.

The percentage error comparison for 3 layers of Boron Nitride spray and 5 layers of black paint is shown in figure (7.15). The emissivity value was set to 1.00 for boron nitride spray and 0.98 for black spray paint.

Figure 7.15: % Error Comparison.

In this case Boron nitride spray has performed better than black spray paint. It can be observed from the figure (7.14) and (7.15) that there is large decrease in the percentage error with increase in the value of emissivity (closer to 1). In fact, this is the minimum error obtained in the experiment test setup. There have been various scenarios to determine performance of system by varying either the number of layers of paints or the emissivities value by keeping the number of layers of paints constant.

Figures (7.16) and (7.17) show the layers and emissivity variation performance, respectively for Boron Nitride Spray. In the layer variation performance, the value of emissivity was kept constant and total number of layers of paint was varying while in emissivity variation performance the number of layers of paint was kept constant and the value of emissivity was varying. There is not much difference with the increase in the number of layers of paint but the increase in the value of emissivity influences significantly on the performance. There is reduction of minimum error from 4.9% to 0.5% with the increase in the emissivity value from 0.94 to 1.00."

Figure 7.16: % Error Comparison.

Figure 7.17: % Error Comparison.

Figures (7.18) and (7.19) show layer and emissivity variation performance for Black spray paint. It can be observed that, there is not much difference with the increase in the number of paint layers, but performance improves with the increase in the emissivity while keeping number of the layers constant.

Figure 7.18: % Error Comparison.

Figure 7.19: % Error Comparison.

The best performance was achieved with 3 layers of Boron nitride spray paint with the emissivity value of 1, which is shown in the figure (7.20). The graph in the pink color is the 3 layers Boron Nitride performance with emissivity of 1 and yellow graph represents the default i.e. without any coating. It can be observed that the significant decrease in the percentage error, in fact less than the one obtained in the literature, which is around 1%.

Figure 7.20: % Error Comparison.

The microcontroller has been programmed to convert the analog signal to digital signal. The variable potentiometer voltage is displayed on LCD screen. In this case too, the best performance was achieved with 3 layers of Boron nitride spray paint with the emissivity value of 1, which is shown in the figure (7.21). The graph in the blue color is the 3 layers Boron Nitride performance with emissivity of 1 and pink graph represents the default i.e. without any coating. It can be observed that the significant decrease in the percentage error, in fact less than the one obtained in the literature, which is around 1%.

Figure 7.21: % Error Comparison.

7.3 PCB's Cooling System Effect

The experimental setup, with the oil based heatsink, proposed in the previous chapter was the best setup. The reason for this is because it can deliver exact temperature at given location by taking into account the heat spreading and distribution, spatial resolution as well as thermal dependent coefficients. Apart from these conditions we have also performed the reference temperature during the experiments by setting it as the atmospheric temperature i.e. 23.4°C. The major issue experienced during the performance of the experiments was the nature of oil flow over the PCB. If the oil flow was not uniform, temperature changes every second over a large range and hence it is required to allow a certain period of time to achieve the accuracy in the obtained results after the oil flow started over the PCB. Hence the results and percentage error obtained at the different time increments during the experiment are listed in table (7.1) and presented in

Figure (7.22). Percentage error is calculated against the ones that are obtained with thermocouple and digital thermometer readings.

Table (7.1) listed the percentage error after 2 minutes of starting of the oil flow. These are the temperature values recorded by camera at different locations of PCB, which are in turn compared with the temperature values obtained by thermocouple. The readings were taken at different spots. The captured thermal profile by the infrared camera system at this interval of time is shown in the figure (7.22).

Table 7.1: % Error after 2 minutes of Oil flow

After 2 minutes	Thermocouple Readings (°C)	IR Camera Readings (°C)	% Error
Resistor	27.4	28	2.18
Heatsink	27.9	26.3	-5.73
Zener Diode	25.3	26.2	3.55
Hot Spot	29.8	30.8	3.35

(a) Hot Spot.

(b) Heatsink.

Figure 7.22: Captured temperature profile after 2 minutes of oil flow.

The board had also been programmed to convert analog signal to digital signal, in order to vary response of the circuit, so that its effect can be seen on thermal map. Table (7.2) listed the percentage error after 2 minutes of starting of the oil flow. The readings were taken at different spots. The captured thermal profile by the infrared camera system at this interval of time is shown in the figure (7.23).

Table 7.2: % Error after 2 minutes of Oil flow

After 2 minutes	Thermocouple Readings ($^{\circ}\text{C}$)	IR Camera Readings ($^{\circ}\text{C}$)	% Error
Resistor	24.5	25.2	2.85
Heatsink	23	24.2	5.21
Zener Diode	25.2	26	3.17
Hot Spot	29.5	31	5.08

(a) Hot Spot. **(b) Heatsink.****Figure 7.23: Captured temperature profile after 2 minutes of Oil flow.**

From the table (7.1) and (7.2), it can be observed that, since the oil flow was not uniform, the temperature measured by infrared camera system was continuously fluctuating. Moreover the average temperature also cannot be found out over a given IC or particular region of the thermal mapping.

After 5 minutes of starting of the oil flow, more uniform oil flow can be expected. The results obtained after this time are shown in the table (7.3) and figure (7.24).

Table 7.3: % Error after 5 minutes of Oil flow

After 5 minutes	Thermocouple Readings ($^{\circ}\text{C}$)	IR Camera Readings ($^{\circ}\text{C}$)	% Error
Resistor	27.4	28	2.18
Heatsink	27.9	28.3	1.43
Zener Diode	27	28	3.71
Hot Spot	30.1	30.8	2.32

(a) Hot Spot.

(b) Heatsink.

Figure 7.24: Captured temperature profile after 5 minutes of Oil flow.

The results obtained after 5 minutes of oil flow for the board when programmed as A/D converter are shown in the table (7.4) and figure (7.25).

Table 7.4: % Error after 5 minutes of Oil flow

After 5 minutes	Thermocouple Readings ($^{\circ}\text{C}$)	IR Camera Readings ($^{\circ}\text{C}$)	% Error
Resistor	26.6	27.2	3.00
Heatsink	28.4	27.2	-2.11
Zener Diode	27	28	3.70
Hot Spot	30.3	30.9	1.98

(a) Hot Spot.

(b) Heatsink.

Figure (7.25): Captured temperature profile after 5 minutes of Oil flow.

By comparing the percentage errors obtained in the tables (7.1) and (7.3) or (7.2) and (7.4), reduction in the percentage error is seen, as there is increase in the uniformity in the oil flow. Therefore, the quality of thermal mapping obtained by infrared system was improved. Figure (7.22) shows the blurred themperature profile with less precision, while the figure (7.24) shows the image with better quality. Similarly, figure (7.23) is of better quality than figure (7.25). The percentage error obtained during the steady state oil flow is shown in the Table (7.5).

Table 7.5: % Error during Steady state Oil Flow

At Steady State	Thermocouple Readings ($^{\circ}\text{C}$)	IR system Readings ($^{\circ}\text{C}$)	% Error
Resistor	27.9	28.2	1
Heatsink	27.2	27.7	1.83
Zener Diode	28	28.4	1.42
Hot Spot	27.9	28.5	2.15

From the Table (7.5), the maximum percentage error obtained is 2.15%, while in the literature [33] the minimum percentage error obtained is 3%. The image obtained during the steady state oil flow is shown in the figure (7.26a-b).

(a) Hot Spot.

(b) Heatsink.

Figure 7.26: IR Camera system Image during Steady state.

Hence by comparing figure (7.26) with figures (7.24) and (7.22), it is observed that heat spreading that occurs on the board due to leakage power is reduced as the oil flow gets uniform.

The percentage error obtained during the steady state oil flow when the board is programmed as A/D converter is shown in the Table (7.6).

Table 7.6: % Error during Steady state Oil Flow

At Steady State	Thermocouple Readings ($^{\circ}\text{C}$)	IR system Readings ($^{\circ}\text{C}$)	% Error
Resistor	28.3	28.5	0.7
Heatsink	27	27.7	1.85
Zener Diode	28.2	28.5	1.06
Hot Spot	28	28.6	2.14

From the Table (7.6), the maximum percentage error obtained is 2.14%, while in the literature [33] the minimum percentage error obtained is 3%. Hence, even the maximum error obtained is better when compared to the minimum error obtained in the literature. The minimum percentage error obtained is 1%. This was mainly due to the change of the oil used in experimental efforts. Most researchers [26] have applied Fluka mineral oil for IR thermography which is having higher density while the Aldrich mineral oil were used in the proposed test setup. The images obtained during the steady state oil flow are shown in the figure (7.27a-b).

(a) Hot Spot.

(b) Heatsink.

Figure 7.27: IR Camera system Image during steady state.

The effect of the oil flow regime is shown in the figure (7.28a-b). This figure represents the significant difference in the captured temperature profile obtained from the IR

system with two oil flow regimes. If the oil flow is turbulent, one can obtain a totally different thermal mapping and correspondingly different values of temperature profile, which are irrelevant to the expected or correct results. Enough period of time should be allowed to let the oil flow get stabilized and have a uniform regime.

(a) Turbulent Flow.

(b) Uniform Flow.

Figure 7.28: Captured temperature profile of Hot Spot.

Similarly figure (7.29a-b) shows the temperature profile of heatsink and its near by region for turbulent and uniform oil flow.

(a) Turbulent Flow.

(b) Uniform Flow.

Figure 7.29: Captured temperature profile of Heatsink.

Correspondingly, the percentage errors obtained during the turbulent flow and uniform flow are compared in the figure (7.30). The variation of percentage error obtained with

uniform oil flow is just between 1 to 2% while variation in percentage in turbulent flow is from -1% to 3.5%.

Figure 7.30: % Error Comparison for Turbulent and Steady or Uniform Oil Flow.

The need of the oil based heatsink can be justified by the figure (7.31). The difference in the images obtained before the oil flow starts and during uniform oil flow circulation is shown in the figure (7.31).

(a) Before oil flow starts.

(b) During oil flow circulation.

Figure 7.31: Captured temperature profile.

Figure (7.31a) shows the temperature profile; hence the exact location temperature of a given device cannot be known. However, it can be seen from the figure (7.31b) that temperature profile is more accurate. Hence temperature at a given specific location i.e.

resistor, zener diode or heatsink can be known and there is no need of calculating the average temperature for any device (by measuring temperatures at different locations of the device).

7.4 Summary

The various experimental setups consisting of FLIR SC 4000 camera system were employed to investigate the temperature distribution on IPB V1.0 (68HC11 Microcontroller Board). The results obtained from the experiments are comparable to the available results to validate the accuracy of this new setup.

First, initial thermal mapping was performed on microcontroller board. It gave the idea to determine the faults on the PCB, due to the change of location of hot spot. Steady state as well as transient analysis was performed to achieve the thermal mapping for a given period of time. The results were not as accurate as available data in the literature. So this gave rise to development of more accurate experimental techniques. The circuit is programmed to display message "HELLO WORLD" on the LCD display. Apart from this, the circuit is also programmed to convert Analog signal to Digital signal (A/D converter) and the results have been validated and discussed.

The second experimental setup was performed on the same board to study the effect of coating and emissivity on the obtained results. Several different combinations of layers of coating of Boron Nitride spray and Black spray paint were deployed with different emissivity settings. Emissivity was controlled manually by trial and error method so as to reduce the error. The comparison of the IR system results was being done with thermocouple readings obtained with the digital thermometer. The error was reduced the 0.5%. Without any coating, the error is around 8%. Performance variation with respect to change in the number of color layer coatings and emissivity values has been executed.

Finally, a general experimental setup that can be employed for any system was proposed. All the parameters affecting the thermal mapping i.e. external as well as internal are addressed in the proposed test setup. New test setup for cooling of the system under test so as to increase the spatial resolution, accuracy, prevent the leakage power distribution, and to know exact junction temperature were also described. The infrared thermal mapping and its corresponding percentage errors were investigated for various

time intervals of oil flow. The need of the oil based heatsink was also discussed and justified with IR thermal mapping system. This setup can be useful to find out the exact device location temperature. Moreover the effect of oil flow regime has been presented. Successful performance of experiments showed that the proposed test setups were stable, reliable and repeatable.

Chapter 8

Conclusion and Future Work

In this thesis, the methodology, implementation and validation of new experimental setup for thermal mapping have been introduced. FLIR SC 4000, which is the Infrared camera, has been applied as optical measurement system. It has the ability to see through the silicon. K-type thermocouple has been also utilized to achieve the reference readings. It is coupled to digital thermometer to read the temperature value. The experimental setup is capable of performing steady state and transient analyses. Moreover it can obtain images at a maximum frame rate of 125 fps with high spatial resolution of $10 \times 10 \mu m$. By making use of various paints for uniform emissivity, as well as oil based heatsink, the proposed method can be practiced in the electronic industry at testing and verification stage.

Thermal mapping on 68HC11 microcontroller was implemented under steady state as well as transient state. Under steady state, thermal map showed the hot spot and heatsink temperatures. Moreover, when two terminals of the capacitor C_{16} were shorted, there was drift in the location of hot spot from GAL IC (Memory Mapped IC). Hence, in case if there is large difference in location of hot spot in any device, or wide variation in the temperature value, one can make out that there is fault in the vicinity of changed location. Apart from that, we can also find power distribution, which can be helpful in changing design if required lower power density is not achieved.

Several experiments have been performed to achieve accuracy. Boron Nitride and Black Spray Paints have been used to create uniform emissivity. Emissivity is controlled by Infrared camera manually in object parameter settings. The results are compared with the ones obtained by thermocouple and digital thermometer. An isolated atmosphere is used for the experiments so as to reduce the disturbance in the images. Atmospheric temperature, reflectivity, humidity, reflected temperature have been set precisely as much as possible to gain the accuracy. Moreover the readings are taken after 4 to 5 hours of gap after which PCB is painted because if the paint is wet, IR camera as well as thermocouple will give the wrong results. The circuit programmed to display simple message as well as to convert analog signal to digital signal, which is displayed on LCD screen.

Cooling of the device has been taken into consideration during the next set of experiments. 161403 Aldrich mineral oil has been used to develop oil based heatsink. This setup is the most recently developed and gives the real time temperature measurement. Its main advantage is the accuracy, it can show the accurate transistor junction temperature, which is desirable. All the issues pertaining to leakage power, spreading of the heat on silicon die and thermal time constants are being resolved in this setup. The time required to wait for achieving the accurate results depends on the system on which we are investigating as well as the accessories available for the experiment. In the setup shown in this work we have tied the pipes to create suitable flow, if specific stands are available for holding the pipes in the steady condition right from the beginning, then uniform oil flow can be achieved at an early stage and readings can be taken.

In general, by this research project we would like to emphasize on the importance of thermal mapping on VLSI circuits. It has been shown that real time thermal testing is critical and must be considered before production or putting the product in the market. The results indicate that experimental setup can quickly find temperature profile on operating device, which is more reliable and authentic, compared to the ones obtained by detailed or compact thermal modeling. Both the above mentioned setups for the uniform emissivity setup and the other one with Infrared transparent heatsink are necessary to test any electronic device before production.

Hopefully in the future by adding more accessories in the experimental setup, we would like to obtain power distribution beneath the VLSI circuit and would also like to achieve the performance rating of the circuit at the operating temperature. We are also interested in performing thermal mapping on High Power density circuits such as motherboards, microcontroller boards that are programmed in a more complex manner. In this work, two different setups have been discussed but in future, we can create arrangements for both facilities in the single experimental setup. I-V characteristics of several devices at different temperature levels needs to be investigated to achieve the significant information of thermal effect. We would like to achieve the power map of the entire circuit board that is in operation. Apart from this we would like to perform similar kind of experiments on high power density circuits, which are used in power electronics application. The true

value of the developed testing method can be achieved through this application. Moreover, same experiments can be performed at the chip level and transistor level to evaluate their performance more closely. Moreover there is provision of software development kit available with Infrared cameras; it can be used for custom programming with infrared camera. Image processing and post processing of parameters can be done with Software Development Kit. We can achieve I-V characteristics of the complete board by modeling the complete board in the form of code in Visual Basic or Visual C++ and by connecting camera to the applications with SDK. Our goal is to improve upon it and to apply it to different research topics in the computer architecture community.

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Appendix 1:

Specification of the SC4000 IR Camera

Read-out Integrated Circuit (ROIC) & Focal Plane Array (FPA)

Indium Antimonide (InSb)– - 320(H) x 256(V) Pixels

Advanced ISC0209 ROIC

30-micron pixel pitch

> 99.5% Operability

Wavelength Range: 3-5 μm (1.5-5 μm optional)

Electronics & Data Rate

320 x 256@ 420 Hz Output

14-bit Digital Data

30 Hz Analog Output Independent of Digital Output (Frame Buffer)

Windowing capability for increases frame rates

Inputs/Outputs

Gigabit Ethernet (RJ-45) for Command & Control/Digital Data Transmission

Camera Link Base for Command & Control/Digital Data Transmission

USB for Command & Control

IRIG-B for time tagging of images, synchronizing to external event– - via BNC

Sync-In for triggering the camera to external device– - via BNC

Sync-Out for triggering external devices to the camera– - via BNC

Genlock for triggering the analog vide– - via BNC

Integration Activ– - via BNC

Analog Vide– - RS-170– - Via BNC

Performance Specifications

25 mK Sensitivity (18 mK typical)

Environmental

One Piece Design

-40 $^{\circ}\text{C}$ to +71 $^{\circ}\text{C}$ Operational

95% non-condensing

Digital Data & Communications

Command & Control (user selectable)

Gigabit Ethernet RJ-45

USB

Camera Link

Data Output (user selectable)

Gigabit Ethernet

Camera link

Physical Specifications

Size (L x W x H)

7.7" x 5" x 6"

Weight

10 lbs

Appendix 2:

Specification of the Digital Thermometer HH-23A

Display: 5-digit LCD; custom indicators for thermocouple type °C/°F units, hold and low battery; HH-22A and HH-23A have additional indicators for input (T1, T2, T1-T2, scan), up/down trend arrows and min/max data storage.

Keypad: Momentary switches with tactile feedback; on/off, thermocouple type, units, resolution, hold; HH-22A and HH-23A have additional keys for record min/max, view min/max, stop/clear record input type (T1, T2, T1-T2, scan)

Configuration Retention: Selected readout, input type, units and resolution retained on power-off

Diagnostics: Low battery, open thermocouple, invalid keypad entry, out of range, internal hardware fault

Accuracy: 0.1% rdg + 0.5°C (1°F)

Repeatability: 0.2°C for 1 week at constant temperature

Resolution: 0.1° throughout entire range

Temperature Coefficient: (0.02% rdg + 0.1°C) below 64°F (18°C) and over 82°F (28°C); included in accuracy, between 18 and 28°C (64 and 82°F)

Ambient Temperature: 0 to 50°C (32 to 122°F), 0 to 90% RH

Reading Rate: 1 per second

Max Common Mode Voltage: 42 V peak to earth ground

Power: 9 Vdc battery, alkaline (included)

Battery Life: 100 h, typical, alkaline battery

Dimensions: 178 H x 74 W x 28 mm D (7.0 x 2.9 x 1.1")

Weight: 284 g (10 oz)

Accessories Included: 9 Vdc alkaline battery, beaded wire Type K probe (for each input), integral tilt stand/ handle, wrist strap, rubber holster, NIST certificate, and operator's manual.

Appendix 3:

Specification of the Oil Pump

- Material: Reinforced polyester/stainless shaft/BUNA rubber impeller
- Gallons per Minute: 3.75
- Self-Prime: 7.5'
- Port Sizes: 3/4" garden hose or 3/8" NPT inlet & outlet
- Draw: 4.7-6A @ 12V DC.

Appendix 4:

* Display "HELLO WORLD" on LCD Screen

bra Main

Hello dc.b "Hello World!", \$0d, \$0a, 0

Main clr COPCTL

lds #USER_STACKSTOP

; Initialize sci

movw #\$0034,SC0BDH

movb #\$00,SC0CR1

movb #\$0c,SC0CR2

ldaa SC0SR1

ldx #Hello

bra L2

L1: brclr SC0SR1,\$80,11

staa SC0DRL

ldaa 1,X+

bne L1

movb #%01111111,PWLCK

movb #%00000001,PWPOL

clr PWCTL

clr PWTST

movw #\$f424,PWPERO

* Display Potentiometer voltage on LCD Screen (A/D Converter)

org \$6000

ADCTL equ \$1030

ADR1 equ \$1031

ADR2 equ \$1032

ADR3 equ \$1033

ADR4 equ \$1034

ADR5 equ \$1035

ADR6 equ \$1036

ADR7 equ \$1037
ADR8 equ \$1038
Result rmb 8

TEN_THOUS	RMB 1; Memory locations used for INT2BCD and BCD2ASC subroutines
THOUSANDS	RMB 1
HUNDREDS	RMB 1
TENS	RMB 1
UNITS	RMB 1
BCD_SPARE	RMB 10
NO_BLANK	RMB 1

org \$7000

jsr clearLCD
ldx #result
jsr convert8channels
ldaa result
jsr convertVoltage
jsr INT2BCD
jsr BCD2ASC
jsr print2LCD
swi

* Get AD Converter voltages and store to memory

convert8channels

psha
ldaa #%00010000
staa ADCTL

wait1

tst ADCTL
bpl wait1

ldaa ADR1
staa 0,x
ldaa ADR2
staa 1,x
ldaa ADR3
staa 2,x
ldaa ADR4
staa 3,x

```
ldaa #%00010100
staa ADCTL
```

wait2

```
tst ADCTL
bpl wait2
```

```
ldaa ADR1
staa 4,x
ldaa ADR2
staa 5,x
ldaa ADR3
staa 6,x
ldaa ADR4
staa 7,x
pula
rts
```

* Convert Battery voltage

convertVoltage

```
ldab #39
mul
add #600
rts
```

* Displays Potentiometer voltage on LCD

print2LCD

```
psha
ldaa TEN_THOUS
jsr writeCharLCD
ldaa THOUSANDS
jsr writeCharLCD
ldaa #'.'
jsr writeCharLCD
ldaa HUNDREDS
jsr writeCharLCD
ldaa #' '
jsr writeCharLCD
ldaa #'V'
jsr writeCharLCD
```

pula
rts

* Subroutines related to LCD (From Lab2)

checkLCDBusy

tst \$1400
bmi checkLCDBusy
rts

clearLCD

jsr checkLCDBusy
ldab #1
stab \$1400
rts

writeCharLCD

jsr checkLCDBusy
staa \$1401
rts

* CONVERSION ROUTINES BY PETER HISCOCK *

* file ref b16todec.asm

*BCD_BUFFER EQU * The following registers are the BCD buffer area
*TEN_THOUS RMB 1 10,000 digit
*THOUSANDS RMB 1 1,000 digit
*HUNDREDS RMB 1 100 digit
*TENS RMB 1 10 digit
*UNITS RMB 1 1 digit
*BCD_SPARE RMB 10 Extra space for decimal point and string terminator
*NO_BLANK RMB 1 Used in 'leading zero' blanking by BCD2ASC

* Integer to BCD Conversion Routine

* This routine converts a 16 bit binary number in .D into

* BCD digits in BCD_BUFFER.

* Algorithm:

* Because the IDIV (Integer Division) instruction is available on

* the 68HC11, we can determine the decimal digits by repeatedly

* dividing the binary number by ten: the remainder each time is

- * a decimal digit. Conceptually, what we are doing is shifting
- * the decimal number one place to the right past the decimal
- * point with each divide operation. The remainder must be
- * a decimal digit between 0 and 9, because we divided by 10.
- * The algorithm terminates when the quotient has become zero.
- * Bug note: XGDY does not set any condition codes, so test for
- * Quotient zero must be done explicitly with CPX.
- * Data structure:
- * BCD_BUFFER EQU * The following registers are the BCD buffer area
- * TEN_THOUS RMB 1 10,000 digit, max size for 16 bit binary
- * THOUSANDS RMB 1 1,000 digit
- * HUNDREDS RMB 1 100 digit
- * TENS RMB 1 10 digit
- * UNITS RMB 1 1 digit
- * BCD_SPARE RMB 2 Extra space for decimal point and string terminator
- INT2BCD XGDY Save the binary number into .X
- LDAA #0 Clear the BCD_BUFFER
- STAA TEN_THOUS
- STAA THOUSANDS
- STAA HUNDREDS
- STAA TENS
- STAA UNITS
- *
- CPX #0 Check for a zero input
- BEQ CON_EXIT and if so, exit
- *
- XGDY Not zero, get the binary number back to .D as dividend
- LDX #10 Setup 10 (Decimal!) as the divisor
- IDIV Divide: Quotient is now in .X, remainder in .D
- ANDB #\$0F clear high nibble of remainder
- STAB UNITS and store it.
- CPX #0 If quotient is zero,
- BEQ CON_EXIT then exit
- *
- XGDY else swap first quotient back into .D
- LDX #10 and setup for another divide by 10
- IDIV
- ANDB #\$0F
- STAB TENS
- CPX #0
- BEQ CON_EXIT
- *
- XGDY Swap quotient back into .D
- LDX #10 and setup for another divide by 10
- IDIV
- ANDB #\$0F

STAB HUNDREDS

CPX #0

BEQ CON_EXIT

*

XGDX Swap quotient back into .D
LDX #10 and setup for another divide by 10

IDIV

ANDB #\$0F

STAB THOUSANDS

CPX #0

BEQ CON_EXIT

*

XGDX Swap quotient back into .D
LDX #10 and setup for another divide by 10

IDIV

ANDB #\$0F

STAB TEN_THOUS

*

CON_EXIT RTS We're done the conversion

* File ref: bcdtoasc.asm

*BCD_BUFFER EQU * The following registers are the BCD buffer area

*TEN_THOUS RMB 1 10,000 digit

*THOUSANDS RMB 1 1,000 digit

*HUNDREDS RMB 1 100 digit

*TENS RMB 1 10 digit

*UNITS RMB 1 1 digit

*BCD_SPARE RMB 10 Extra space for decimal point and string terminator

*NO_BLANK RMB 1 Used in 'leading zero' blanking by BCD2ASC

* BCD to ASCII Conversion Routine

* This routine converts the BCD number in the BCD_BUFFER

* into ASCII format, with leading zero suppression.

* Leading zeros are converted into space characters.

* The flag 'NO_BLANK' starts cleared and is set once a non-zero

* digit has been detected.

* The 'units' digit is never blanked, even if it and all the

* preceding digits are zero.

BCD2ASC LDAA #0

Initialize the blanking flag

STAA NO_BLANK

*

C_TTHOU LDAA TEN_THOUS	Check the 'ten_thousands' digit
ANDA #\$0F	Clear the high nibble
ORAA NO_BLANK	
BNE NOT_BLANK1	
*	
ISBLANK1 LDAA #' '	It's blank
STAA TEN_THOUS	so store a space
BRA C_THOU	and check the 'thousands' digit
*	
NOT_BLANK1 LDAA TEN_THOUS	Get the 'ten thousands' digit
ORAA #\$30	Convert to ASCII
STAA TEN_THOUS	
LDAA #\$1	Signal that we have seen a 'non-blank' digit
STAA NO_BLANK	
*	
C_THOU LDAA THOUSANDS	Check the thousands digit for blankness
ANDA #\$0F	Clear the high nibble
ORAA NO_BLANK	If it's blank and 'no-blank' is still zero
BNE NOT_BLANK2	
*	
ISBLANK2 LDAA #' '	Thousands digit is blank
STAA THOUSANDS	so store a space
BRA C_HUNS	and check the hundreds digit
*	
NOT_BLANK2 LDAA THOUSANDS	(similar to 'ten_thousands case)
ORAA #\$30	
STAA THOUSANDS	
LDAA #\$1	
STAA NO_BLANK	
*	
C_HUNS LDAA HUNDREDS	Check the hundreds digit for blankness
ANDA #\$0F	Clear the high nibble
ORAA NO_BLANK	If it's blank and 'no-blank' is still zero
BNE NOT_BLANK3	
*	
ISBLANK3 LDAA #' '	Hundreds digit is blank
STAA HUNDREDS	so store a space
BRA C_TENS	and check the tens digit
*	
NOT_BLANK3 LDAA HUNDREDS	(similar to 'ten_thousands case)
ORAA #\$30	
STAA HUNDREDS	
LDAA #\$1	
STAA NO_BLANK	
*	
C_TENS LDAA TENS	Check the tens digit for blankness

ANDA #\$0F
ORAA NO_BLANK
BNE NOT_BLANK4

Clear the high nibble
If it's blank and 'no-blank' is still zero

*

ISBLANK4 LDAA #' '
STAA TENS
BRA C_UNITS

Tens digit is blank
so store a space
and check the units digit

*

NOT_BLANK4 LDAA TENS
ORAA #\$30
STAA TENS
LDAA #\$1
STAA NO_BLANK

(similar to 'ten_thousands case)

*

C_UNITS LDAA UNITS
ANDA #\$0F
ORAA #\$30
STAA UNITS

No blank check necessary, convert to ASCII.

*

RTS

Done!