TERAHERTZ AND LASER IMAGING FOR PRINTED CIRCUIT BOARD FAILURE DETECTION

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Abstract – This paper describes research and development efforts in the application of advanced optical techniques for prognostic analysis of printed circuit boards and their components. Current methods of automated electronic testing require development of costly unique Test Program Sets (TPSs) for each type of board, and only return information related to the current performance characteristics. The use of laser diagnostics in circuit board testing can eliminate the need for TPSs, while identifying compromises in material integrity that will lead to hard and soft component failures. Additionally, they may be applied to solve instances of retest OK (RTOK) and no-fault-found events. Our investigation has focused on Terahertz (T-Ray) imaging, laser acoustics, and near-infrared (NIR) laser imaging. T-Ray imaging is an emerging laser-based technology characterized by the ability to "see through" layers of plastic to the embedded metal traces of a circuit board or to the die of an encapsulated microchip. Laser acoustics may be applied to monitor the integrity of solder joints, and NIR laser imaging may be used to identify damage within an integrated circuit (IC). We present the results of our investigation into the combined use of these techniques for fault diagnosis, as well as their relative potential in the electronics test industry.

INTRODUCTION

The technique of passive imaging and inspection for detecting printed circuit board failures has typically focused on detecting structural board defects and component interconnect failures. However, with the recent advances in the realm of terahertz band imaging, new possibilities exist for identifying a larger scope of failures.

In this paper we present our approach for applying imaging techniques that utilize radiation from the near-infrared, terahertz, and acoustic regions of the electromagnetic spectrum. Each of these regions has specific capabilities in terms of potential for detection of the various classes of defect as well as imaging resolution. This paper is organized in the following manner. First we first analyze the types of defects and failure modes commonly found in PCB's. This step is necessary in order to develop a comprehensive approach to identifying failed printed circuit boards because it allows fault signatures to be developed that correspond with the detection capabilities of a particular signal. After this we discuss the imaging modes available with the different regions of the spectrum and their application to detection of particular defects. Following this we present some initial results towards detecting defects. And finally, we give conclusions about the approach.

COMPONENT FAILURE MODES

The major field failure modes for operational PCBs involve discrete contributions from dynamic changes in chemical properties and material microstructure. For our experimental work, we have divided electronic reliability failures into three main classes: chip or IC level, board level, and the device/board junction. A substantial amount of the IC field-failures are caused by electrical overstress (EOS) or electrostatic discharge (ESD), which may manifest as instantaneous, intermittent, or latent defects. It is possible for a device to operate within specifications for a long period of time following a damage event, before

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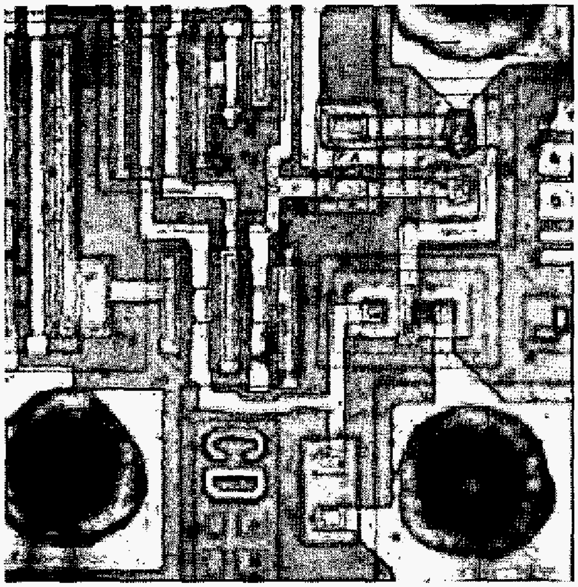
exhibiting an unpredicted field failure. EOS damage may occur due to a reversal of voltage input polarity, a short circuit, or "hot swapping" a powered board. Improper handling is the leading contributor to ESD damage. Sliding an electronic device on a surface, opening a plastic bag, or transporting a device across the floor on a cart may generate voltages as high as 12KV. This is approximately 2400 times the normal operational voltage of ICs.

Integrated Circuit Failures

At the root of the EOS and ESD failures is damage to the materials essential to the operation of the device. Bond wire melting, metallization diffusion, and dielectric breakdown are all associated with the thermal shock that accompanies a voltage surge. Additionally, the transistor materials may be forced to uptake an inappropriate charge, resulting in a stuck high or low output position called latch-up. This may be a temporary or permanent type of damage.

Figure 1. Example of ESD Damage



An example of the difficulty in assessing EOS and ESD damage in ICs is illustrated in Figure 1. The image shows a portion of a decapsulated DIP (a NAND device). To simulate a field-failure, it was subjected to a static discharge from a piezo static generator directed to one of its input pins. Damage is visible in the areas where the metallization and transistor regions meet. Although damage of this extent would appear to be catastrophic in nature, the NAND gate was first observed to be in a latch-up state when tested, and then functioned normally, followed by intermittent operation.

Printed Circuit Board Defects

Board level defects that cause field-failures include delaminations, damage due to mechanical stress, and metal-ion migration. A delamination of the composite layers of a circuit board may be a result of overheating encountered during operation environments or soldering by repair personnel. These reduce board integrity and can permit moisture to pervade its structure, thereby increasing the probability of metal migration.

The delamination shown in Figure 2 is observable (upper left quadrant) with visible examination or microscopy, however in poly-layer boards the delamination may be internal and invisible to inspection routines. Mechanical stress from vibration, recurring insertion/removal, or thermal cycling leads to cracks in circuit boards. Figure 3 is an example of a stress crack produced in a board by mechanical deformation. Cracks in a board can propagate to the metal traces creating open circuits, or allow moisture absorption within the matrix.

Figure 2. Example of Delamination Damage

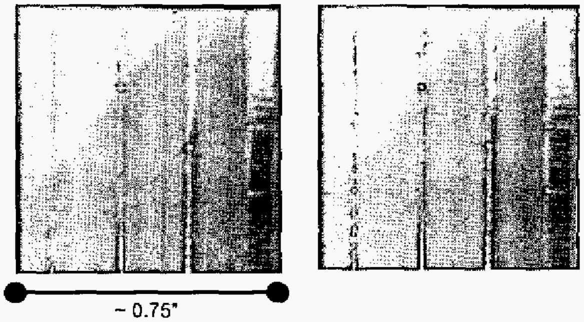
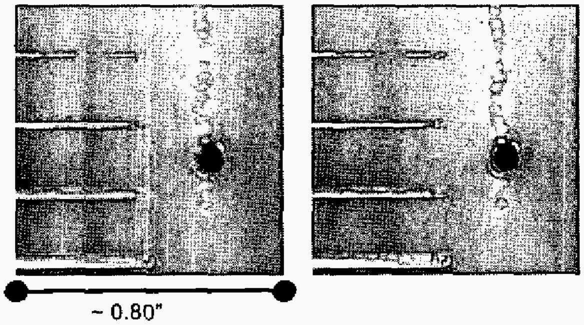


Figure 3. Example of Stress Cracking



Manufacturing and environmental factors lend to conditions conducive to ion migration on and within PCBs. Ion migration is the phenomena of precipitate metal dendrite growth between electrodes and traces on boards, the result of an undesired electrochemical reaction [1]. The effects of this metal bridging between contacts are hard or soft failures creating short-circuits and arcing or intermittent loss of current flow. The latter is usually a culprit in retest-ok (RTOK) scenarios, as the dendrites are very fragile and may exist for only a short instant. Three factors that collectively cause electrochemical corrosion in PCBs are: 1) ionic surface contaminants, 2) electrical potential (applied voltage), and 3) moisture or high ambient humidity.

Migration occurs when moisture adheres between metal electrodes and dissolves ionic contaminates, resulting in a solution capable of conducting electric current and supporting metal migration. Copper atoms are very susceptible to electro-migration, as are silver, lead, and tin. Progress has been made on the manufacturing end of PCB reliability to limit the amount of ionic contaminants present on a final product. However, older generation boards manufactured prior to these advances are and will be in service for many years to come, and are susceptible to sources of ionic contaminants. In addition, the reworking of solder on older and expensive PCBs is common in military applications, and introduces new contaminates to a component that may have been deemed "clean" prior to rework. Unqualified personnel performing repairs with substandard materials often increase the likelihood of this scenario and contribute to field failures.

Environmental factors are a major source of contaminants that promote diffusion of metal atoms and lead to field failures. Air pollution, fumes from exhaust, degradation products of nearby components, sea spray, and improper handling by maintenance personnel contribute to the presence of ionic substances on the surface of PCBs in operation. Humid operating conditions (over 50% relative humidity) encourage the formation of a microscopically thin film of condensed water on the surface of a PCB, thereby lowering surface resistance. The higher the humidity, the thicker this moisture layer is and the faster corrosion or dendrite growth can occur.

Component Interconnect Failures

The junction between components and the board is an area where a large amount of field failures occur. Electronic components are mounted to PCBs with solder joints that provide both electrical and mechanical connections. Especially in demanding military and space environments, solder joints deteriorate over time with exposure to mechanical stress and thermal cycling; the latter believed to be a larger contributing factor. Mismatch between the coefficients of thermal expansion (CTE) between PCB materials lead to failures in electronics hardware due to overstress and cyclic fatigue damage. Phase changes within solder material at elevated temperatures also contribute to solder cracking and delamination [2].

Solder fracture can occur internally within the solder or at the area where solder joins another surface. Both types are known to occur in the field and are responsible for a major portion of electronic equipment failure. The diagnostics of solder fractures are difficult, as fully fractured solder joints do not result in steady-state open circuit defects. Rather, the faulty solder joint causes intermittent performance failures and circuit malfunctions, leading to RTOK and no-trouble-found (NTF) scenarios. The intermittent character is inherent due to the construction of the board: neighboring intact solder joints keep the component in place and the faulty joint under compressively loaded contact for the most part. Additionally, service conditions such as mechanical vibration or shock and the torsions from thermal expansion increase the likelihood of discontinuity, and are usually not recreated in diagnostic test scenarios.

IMAGING TECHNIQUES

In order to detect failures across the broad range of possible failure modes, different imaging techniques are utilized. The application of imaging technique proceeds in the order of visible light, acoustic, terahertz, and IR laser. This order of image acquisition is based upon a coarse to fine resolution approach, whereby boards are first scanned using the lowest resolution technique first and progressively resolution is increased. In this manner, gross board level failures or defects are identified first, when they exist, in order to home in on regions requiring more detailed evaluation. The exception to this approach is the visible light scan of the board. Although this is the

highest resolution, it includes the distinct wavelengths corresponding to color. The visible light mode allows segmentation of the image based upon known object type, such as PCB, trace, solder joint, and IC encapsulating materials. Once the segmentation has been performed, the additional imaging techniques are applied.

Infrared Laser Imaging

The transparency of an integrated circuit's silicon substrate to radiation in the near infrared (NIR) spectrum permits a non-invasive method for imaging the component circuitry of the IC. The NIR spectrum begins just outside the visible light region, and spans the wavelengths between 700 nm and 2500 nm. According to experimental research [3], the region of maximum transmissivity occurs at approximately 1000 nm (1 micron). This coincides with the readily available Nd:Yag lasers that output 1064 nm wavelength radiation at a broad range of intensities in either continuous or pulsed form. Furthermore, inexpensive NIR optimized CCD cameras, as opposed to the significantly more expensive InGaAs based camera, are available for acquisition of images.

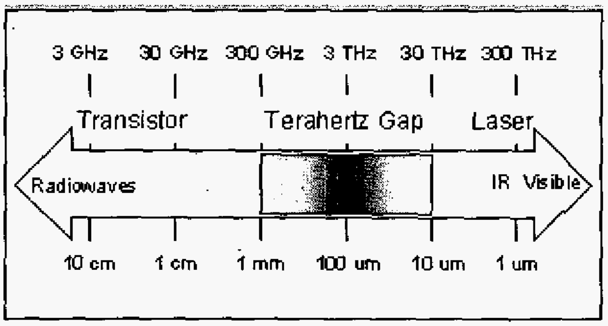
The maximum resolution attainable at the wavelength NIR wavelength λ is approximately 0.6λ. Since the smallest features of high density ICs may be significantly smaller than 1 micron, higher resolution is necessary. One technique under investigation requires the insertion of an additional lens between the normal camera lens and the silicon substrate. This approach is based on the use of a solid immersion lens (SIL), which is discussed by Mansfield and Kino [4] as the basis for a solid immersion microscope. By reducing the loss in resolution that results from the interface between a high index of refraction material and air, resolution can be improved by a factor of 1/n. This would allow imaging of features inside of silicon with resolution comparable to ultraviolet light [4].

Although many ICs are encapsulated with a packaging material, the trend in recent years has been to package high-density ICs in the "flip-chip" package. Flip-chips are ideal candidates for laser-based analysis, since this type of chip is mounted with its silicon substrate facing up, away from the mounting surface. This provides a direct line of access through the silicon substrate to the ICs transistors, since all wires and metallization are near the top of the chip.

Terahertz Imaging

Terahertz imaging has in recent years received much attention due to its inherent capabilities of "seeing through" many types of non-metallic material. The terahertz (THz) portion of the spectrum lies in the range from approximately 300 GHz (0.3 THz) to 30 THz (see Figure 4). However, exploiting the full potential of the terahertz region of has been particularly difficult. This region of the spectrum is often referred to as the "terahertz gap," because of the lack of efficient sources and detectors of terahertz radiation. On the one hand, transistors and other quantum devices based on electron transport are limited to about 300 GHz, and on the other hand, the wavelength of semiconductor lasers can be extended down to only about 10 um (or 30 THz).

Figure 4. Terahertz Gap



Nevertheless, recent advances in the design of compact, efficient sources and detectors have opened up new possibilities for terahertz imaging. Current generation devices are based upon titanium-sapphire lasers which are relatively expensive (approximately $100K). But new device designs are being developed based upon quantum cascade and germanium hole inversion lasers which are relatively cheap, efficient, and capable of power output in the low to mid milli-watt range [5].

The two modes of imaging available using terahertz radiation are reflection and transmission mode; however the techniques for acquiring images are similar for both modes. In transmission mode, the acquired image is the result of any radiation that was not completely blocked or absorbed, whereas for reflection mode the image is created from the reflected energy. Because different materials attenuate terahertz radiation to different extents, the variation in amplitude can be measured to create an image.

Furthermore, since the terahertz pulse covers a broad frequency spectrum and is hence very narrow in time (sub-picosecond), the transit-time of the THz pulse can also be measured. This is also known as a time-of-flight measurement. The time of flight measurement effectively measures the change in optical path length that occurs either due to variation in thickness of the sample or changes in the refractive index.

These techniques and imaging modes are collectively characterized as terahertz time-domain spectroscopy (THz-TDS), or T-Ray imaging. Currently, most THz-TDS time-domain imaging systems are constructed using a basic system template that consists of a femtosecond laser, an optically gated terahertz transmitter and receiver, a computer controlled optical delay line, collimating and focusing optics, and a DSP controlled by a computer. One of the major disadvantages of the current approach to T-ray imaging is with the optical delay line. The imaging of a sample requires that the delay of one optical beam relative to a second beam be varied in order to move the sampling gate across the waveform to be sampled. This is commonly done through the mechanical process of varying the optical path length traversed by one of the beams, either by stepper motor or high-speed actuator. The actual speed of the scanning process determines the data acquisition rate. Due to limitations in the rate at which the scanner can traverse the displacement of approximately 1.5 cm, most pixel-by-pixel terahertz image acquisition devices operate at around 20 Hz, or 20 pixels per second.

The application of terahertz imaging for detecting failures in printed circuit boards and electronic components is feasible for many types of failures. EOS or ESD mechanisms contribute to a large number of integrated circuit failures. A catastrophic failure may result in relatively large-scale delamination or other deformation that still remains hidden during visible light inspection. And non-catastrophic failures often result in modification of substrate or trace properties. Using reflection mode THz imaging, detection of such damage in integrated circuits is possible down to a spatial scale of approximately 100 microns. On the scale of the entire printed circuit board, stress related cracking and board layer delamination are candidates for detection with terahertz imaging. While IC imaging can be performed primarily in reflection mode, board level imaging can be performed either in reflection or transmission mode. The determining factors are the number of composite layers of which the board is constructed and whether the number and density of metal layers permits adequate information to be acquired. Finally, in-situ imaging of PCBs requires interpreting the imaging results of complex boards with multiple components. Currently we are performing tests on terahertz imaging of boards with known features and defects in order to determine the full extent of capabilities.

Acoustic Imaging

Although solder joint failures comprise a large percentage of field failures in electronic components, an automated method to specifically analyze the integrity of these parts in the field remains elusive. Laser acoustic vibrometry is a viable option for field-testing solder joints on electronics, as demonstrated by a group at Georgia Tech [6]. In this method, a pulse from an infrared laser is aimed at a UUT, to induce a minute structural vibration within the component. A second laser, part of an interferometer instrument, is also aimed at the surface and measures any displacement of the UUT during the vibration. The vibration response is dependent on the nature of the bonds between the device and the board. Components with defective solder joints yield different vibration signatures than those with healthy joints. This method is different from the other techniques described in this paper, as it is not an imaging technique. Rather, it uses signal processing and pattern analysis to classify defects that may not be identified with electrical tests.

Laser vibrometry is a non-contact, non-destructive analysis technique. An advantage of laser diagnostics over traditional ultrasound is that no coupling medium is necessary between the device and instrument. This removes a parameter that introduces foreign material to a circuit board, as well as uncertainty and extended time into measurements.

While not strictly considered an imaging technique, acoustic analysis requires many of the same processing techniques that are applied to image analysis. Spatial resolution is on the order of board-level component interconnect size. Laser vibrometry has been applied extensively in the automotive, aerospace, and construction industries for structural analysis, and is poised to make an impact in the automated field-testing industry for electronics.

IMAGE ANALYSIS RESULTS

The acquisition of image data constitutes the first step in detecting defects in ICs and PCBs. The second step is analysis of the resulting images. The approach we have developed utilizes signature functions in conjunction with homomorphic filtering and image differencing techniques. We tested our approach by first inducing an ESD failure in a quad-4 input NAND IC that exhibited the symptoms of RTOK. The integrated circuit was decapsulated and the circuitry exposed.

The original circuit before damage is depicted In Figure 5. It is a small region of the IC near a solder pad that connects the IC leads to the IC.

Figure 5. Original Undamaged Circuits

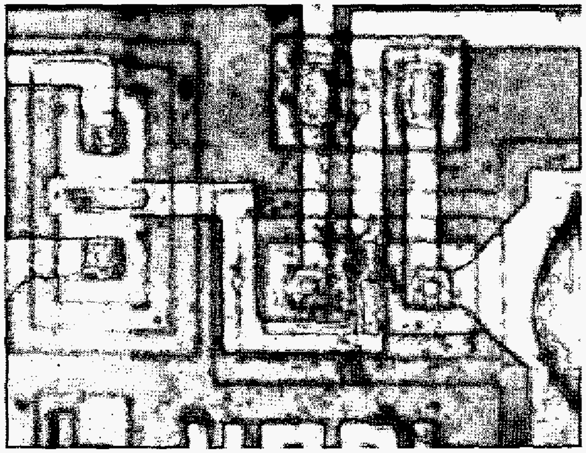
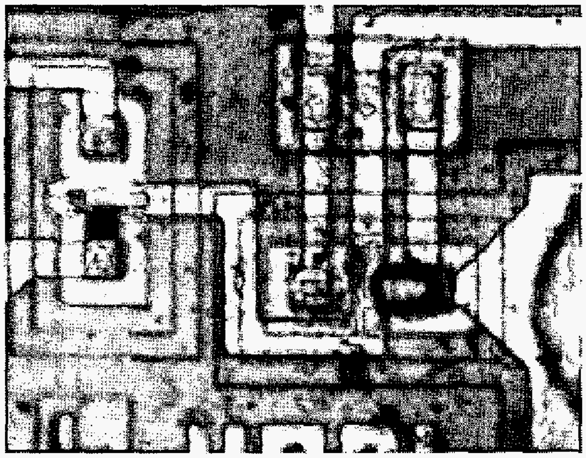


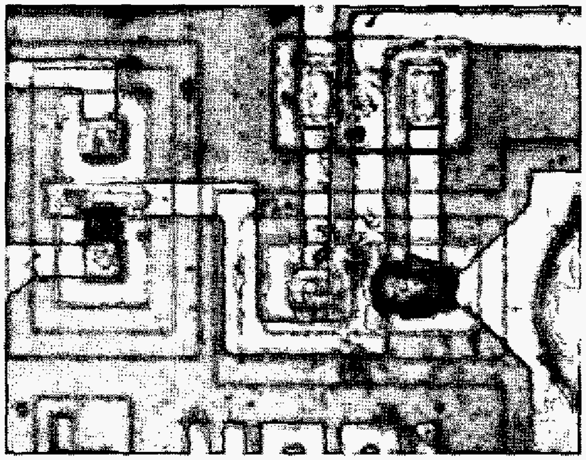
Figure 6 shows the same region of the IC after having been exposed to ESD.

Figure 6. ESD Damaged Circuits



Upon visual inspection, it is apparent that several regions of the IC have undergone physical change. These are the darkened regions near the contact pad and the internal IC traces, as well as additional other trace interconnect regions. Finally, Figure 7 shows the same region after having undergone automatic analysis. All of the regions that have undergone physical change have been identified.

Figure 7. Damaged Circuits Identified



Some additional work that needs to be performed includes validating the defect identification results through physical analysis of the defect region to Also, application of the image analysis approach must be adapted to the types of images that will be acquired using NIR laser and terahertz imaging techniques.

CONCLUSIONS

The approach presented in this paper takes advantage of the unique interaction between electromagnetic radiation in different regions of the spectrum and printed circuit board components for detecting failures in a passive manner. We have investigated the various component failure modes of printed circuit boards and components in order to quantify the defect generation process. Many of the types of defects that commonly occur in printed circuit boards have unique physical signatures that are detectable using one or more imaging techniques. These imaging techniques are applied in manner that permits large scale defects to be detected first, using the lowest resolution imaging mode, with increasingly higher imaging techniques applied for identifying smaller scale defects. Among the

hardest to detect of defects using the currently predominant approach of TPSS are those that lead to RTOK situations. These cases often cannot be resolved with electronic testing, and yet certainly have an underlying physical defect as a cause.

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