COMPARING SHADOW MOIRÉ AND DIGITAL FRINGE PROJECTION WARPAGE METROLOGY TECHNIQUES

Neil Hubble
Akrometrix
Atlanta, GA, USA
nhubble@akrometrix.com

Leon Weaver
Akrometrix
Atlanta, GA, USA

ABSTRACT

Shadow Moiré (SM) remains the most popular metrology approach to measuring surface shapes under dynamic temperature change in the microelectronics industry. Digital Fringe Projection (DFP) is another warpage metrology approach also used in the industry for surface shape over temperature. While some previous studies have compared the techniques, the technology for these technologies has changed over time, thus this study is pursued with implemented improvements in these technologies. Focus is placed on strengths and weaknesses of each technology, and, where applicable, where technology improvements have affected the contrasting strengths and weaknesses of the technology. Specific applications involving unpainted surfaces, discontinuous surfaces, and variable kernel size data smoothing are considered.

Warpage measurements are performed in a controlled environment using the same metrology equipment with only the optical metrology changed between the two techniques. Using the same oven for both technologies is critical for warpage comparisons. Under this controlled environment, multiple samples are tested for warpage over temperature in order to show statistical relevance of data between the techniques, as well as find specific examples where the techniques have comparable or dissimilar warpage measurements. Shadow moiré data is processed using a greater camera bit depth than previous studies, along with new software to work with shadow moiré and discontinuous surfaces, historically an area where only DFP could be used to measure across sudden height changes.

Key words: Warpage, metrology, shadow moiré, digital fringe projection

INTRODUCTION

By no means is this the first attempt to compare SM and DFP. "Comparing Techniques for Temperature-Dependent Warpage Measurement" is one such study from 10 years back comparing warpage metrology techniques, looking at SM, DFP, and digital image correlation (DIC). [1] It would not be the last technical paper or publication comparing warpage metrology techniques. However, technologies change with the times, in some cases rapidly, and as such, comparisons between technologies can also change. Here, we first cover the historical advantages and disadvantages of SM and DFP. Data is then presented matching the techniques head to head, including a warpage over temperature case study. Finally, recent technological updates to each technique that affect these advantages or disadvantages are presented. It is also worth noting that other metrology techniques for thermal warpage measurements may be viable solutions. For the purpose of this paper, value is only added in comparing SM and DFP.

BACKGROUND

Industry standards specific to package warpage over temperature were primarily founded around the use of SM as a measurement technique. Specifically, JESD22-B112A was originally released in 2005 featuring only SM and in 2009 added DFP, along with DIC and Laser Reflectometry techniques. [2] Similarly, JEITA ED7306 sites only SM and Laser Reflection as viable options for measurement package warpage over temperature. [3] On the PCB side of the surface mount attachment, IPC 9641 lists SM, DFP, Confocal Methods, Optical Coordinate Measurements, and DIC, though discredits DIC for PCB flatness measurements. [4]

Numerous technical studies relating to warpage measurement have been performed using the SM technology. Studies coming out of major companies, including: Samsung [5] [10], Nokia [6], Intel [7], SPIL [8], and Huawei [9] show SM is commonly used in understanding thermal warpage effects. While DFP is less frequently used in thermal warpage measurement, the concepts of the technique are also increasingly popular on Solder Paste Inspection (SPI) tools and 3D AOI (Automated Optical Inspection) tools used in SMT production lines. The popularity of this technology in a larger industry than that of thermal warpage should only be advantageous to the progression of the technology. Also, DFP is commonly used in measuring thermal warpage on samples with discontinuous surfaces, as is discussed later.

The SM technique measures surface height by shining a line light through a grating, which is a Ronchi ruled piece of glass having line pitches commonly between 50-500 microns. The interference pattern between the lines and shadow cast by the same lines creates a contour map used for measurement. A

*Originally presented at SMTAI 2017.

phase stepping technique is applied for increased resolution, where camera images are captures with different distances between the grating and sample. Figure 1 shows a conceptual image of the behavior of light in SM, and Figure 2 shows a contour pattern created by SM.

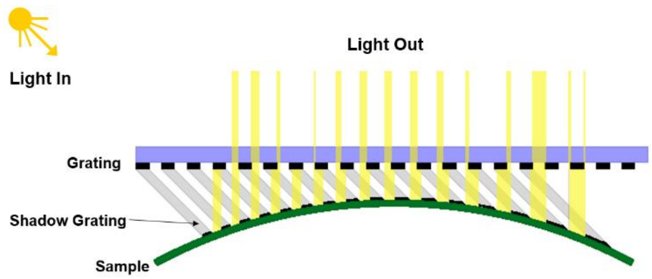

Figure 1. Shadow Moiré Visual Concept

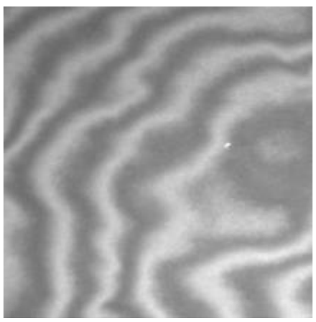

Figure 2. Shadow Moiré Pattern

The DFP technique measures surface height using similar concepts to the SM technique. Instead of creation of an interference pattern, dark and light lines or "fringes" are projected onto the sample from a projector which is at a specific location and angle from a camera. The technique uses a calibration procedure where a flat surface is measured at multiple distances from the projector. The pattern from this calibration is used to contrast with images taken of the sample surface. A phase stepping approach is also used in this case. Fringe density can be varied, limited by the projector resolution only. Figure 3 shows a visual representations of DFP and Figure 4 shows a surface with a few dome shapes and projected fringes.

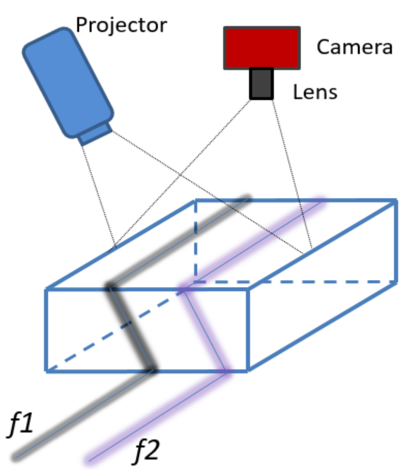

Figure 3. Digital Fringe Projection Visual Concept

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Figure 4. Digital Fringe Projection Pattern

HISTORICAL ADVANTAGES AND DISADVANTAGES

While SM and DFP can be often be used to get similar data on similar applications, each technique has some inherent advantages and disadvantages. Many times using one technique is advantageous over the other depending on the sample under test. A key focus of this paper is in highlighting areas where the technology has changed or is changing. First we begin with some generalized advantages and disadvantages in Table 1.

Table 1. SM vs DFP Advantage/Disadvantage

Shadow Moiré	
Advantages	**Disadvantages**
- Z-resolution independent of FOV - Can reach sub-micron Z-resolution - Less measurement noise - Robust with simple calibration - Acquisition under 2 seconds - Continuously variable FOV	- Grating heat sink effect above the sample - Cannot measure sudden height changes - Working distance limited by highest part of sample - Lower data density - Mechanical phase shifting
Digital Fringe Projection	
Advantages	**Disadvantages**
- No requirements for glass near the sample - Sudden height changes can be measured - Raised surfaces around the ROI are manageable unless shadowed - High data density - Digital phase shifting - Variable acquisition time, can be shorter than SM	- Z-resolution becomes worse as FOV increases - Lacks submicron resolution - Higher noise levels during measurement - Calibration can be complex, particularly if changing FOV - Variable acquisition time, at times longer than SM - Fixed FOV only

Shadow Moiré Key Limitation Details

To make an SM measurement you need to place a grating within a certain distance of the sample surface. The presence of the grating is both critical to the SM measurement and the source of the main limitations of the technique.

Getting close enough to the surface needed for warpage measurement at times is simply not possible. User may not be able to measure assembled PCBs or shielded samples with recessed components using SM. This working distance can range from 30mm down to under 1mm depending on the grating pitch. This is a trade-off, as fine pitch gratings provide better pixel density and lower Z-resolution (sometimes called out-of-plane resolution or warpage resolution), but also require shorter working distances. The physical grating proximity can also play a role in abilities to heat the sample evenly. Recent technology improvements have nearly eliminated this disadvantage and will be discussed further later.

Due to the fringe counting approach of SM, sudden changes in height can lose the fringe count. Thus measuring on balled sample surfaces and many sockets and connectors may not be reasonable for measurement with SM. In contrast, the ability of DFP to project varying period fringe patterns allows for capturing of sudden height changes. Recent technology improvements have expanded the applications with which SM can measure discontinuous surfaces. This technology, called phase bridging, is covered further later.

Finally, data density has specific limitations based on the SM grating pitch. Essentially you cannot zoom into a sample to the point where the grating lines themselves are resolved. At the time of this writing no improvements past this limitation are known. In contrast, DFP has minimal limitations in terms of data density, bottlenecking with data quantities or cost consideration in camera pixels. One detail is often overlooked in regards to data density between SM and DFP. Given specific optical constraints in the design of a DFP system, FOV of system and lensing is fixed. It is certainly possible to have multiple FOV options for a DFP system, but this requires change over time and volumetric recalibration when changing to specific FOV options. Depending on how the sample size matches with the FOV options, the data density may not be maximized for the sample. In contrast, SM can be zoomed in and out with a variable zoom lens so that data density, while still worse than DFP, can be optimized for each setup without recalibration. Data density is covered further later.

Digital Fringe Projection Key Limitation Details

The focal point of DFP limitation is based on how many projected pixels are available to make a fringe pattern. The concept is not unlike a TV projector on a screen. The further you back up the projector the larger the pixel size. There is certainly more than one way to handle the fringe pattern projection. The project pattern can be binary or sinusoidal. The projection can have a single frequency, multiple projected frequencies, or use Gray code for fringe registration of larger steps. The projected pattern can even be intentionally out of focus to a certain degree. Regardless of the approach, the critical limitation in relation to Z-resolution is the physical size of the projected pixel on the sample surface. You need at least one pixel to make a dark or light line, though a one pixel line would not leave much to phase shift. Practically fringes may be closer to 8-16 pixels to define a full phase cycle. As the field of view (FOV) increases, such as in Figure 5, the value associated with each fringe will increase along with the Z-resolution.

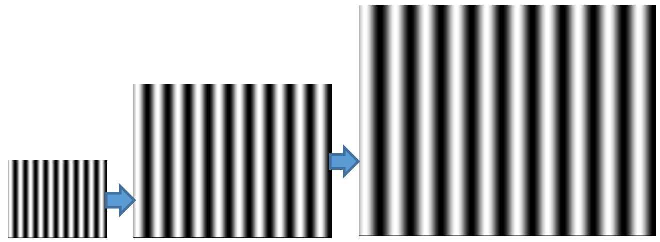

Figure 5. Increase DFP Sizes on Flat Surface

In theory this limitation could be addressed by a multitude of higher resolution projectors and optics, but at some point cost or simply physical space may be prohibitive. This is discussed further later. In some DFP techniques and approaches the Z-resolution has been equated to 1/10,000 of the FOV. When considering SM Z-resolution vs. FOV some practicality comes into play with SM and using fine pitch grating over large areas due to working distance constraints. However, in general the FOV is near immaterial to the Z-resolution with SM. Table 2 shows Z-resolution vs. FOV using the 1/10,000 rule for DFP and practical SM grating setups. Again it is expected that the 1/10,000 relation between FOV and Z-resolution for DFP can be improved upon.

Table 2. Z-Resolution vs. Field of View

FOV (mm)	DFP Z-Res (μm)	SM Z-Res (μm)
600x600	60	2.5
400x400	40	1.25
250x250	25	0.85
100x100	10	0.85
50x50	5	0.5
25x25	2.5	0.5

A final point to be made with DFP is that step height measurement does not come inherent with the technology. Specific approaches need to be taken with multiple patterns or Gray code approaches to correctly register fringes. The need for additional measurements and acquisition cycles can increase the measurement time of the technology. Given that SM and DFP are commonly used for dynamic warpage over temperature, keeping measurement timing minimized is critical. It is difficult to list a specific timing for a DFP measurement, as different approaches require different timing. Through personal observation 1, 4, and 12 second timings have been seen. Physical changes in the measured sample surface during this acquisition time will cause inaccuracy in the measurement.

*Originally presented at SMTAI 2017.

KEY POINTS OF COMPARISON

Having covered conceptual differences between SM and DFP, real test data is used to compare the techniques on key variables using current technology.

Z (Warpage) Resolution

The unfavorable resolution of DFP at larger FOVs is not studied in detail in this paper. The fundamental concept of fringe value scaling with projected pixel size speaks for itself. Instead SM and DFP are compared at a moderate FOV with SM at a 174x120mm FOV using the 200LPI grating and DFP at a 64x48mm FOV. Theoretical resolution for this setup for SM is 1.25 microns and for DFP 5 microns. This setup is used for comparison in other sections of this study.

In order to experimentally test measurement resolution two samples are measured at room temperature. The first sample is a single step metal block with two surfaces flat to within 2 microns and a step height between the two surfaces of 6 microns. The metal surface has acceptable diffuse light reflectance for optical measurement. The second sample is an optical flat that has had a chemical etch applied to the surface in order to create specific features having 3 micron, 1 micron and 0.4 micron depths. The optical flat surface was then coated with a highly uniform sputtering technique that leaves a specular surface that has enough light diffusion to allow for measurement with no further coating. Both samples were measured with point measurement tools after their final processing step, having accuracy an order of magnitude greater than the SM accuracy. Measurement results for the 6 micron step are shown below in Figures 6 and 7.

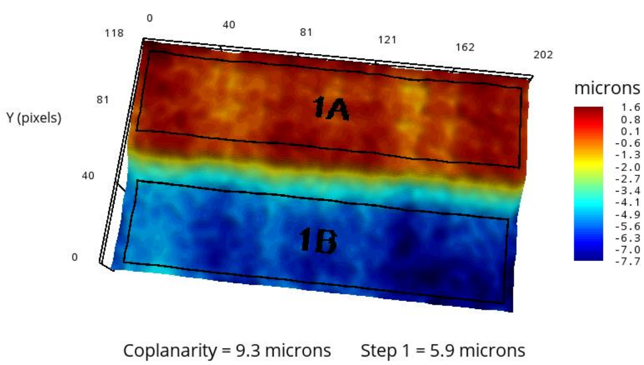

Figure 6. SM on 6 micron step

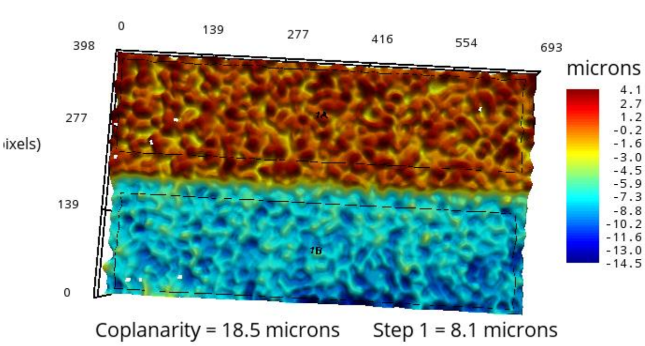

Figure 7. DFP on 6 micron step

Note that the Z scale is different in Figure 6 and 7. Step height measurements are taken by analyzing the average height of the majority of the step region. The 6 micron step is resolved with the DFP technique and is measured at 8.1 microns. However, the coplanarity value is 18.5 microns due to the noise level of the DFP image. This coplanarity was as high as 26.8 microns in the DFP images prior to an 11x11 kernel moving average smoothing function, applied to the data two times. SM data in Figure 6 shows a 5.9 micron step height for the 6 micron step and a 9.3 micron coplanarity. A minor amount of phase shift error can be seen on the flat surfaces at this scale, but all effects are below the theoretical resolution of 1.25 microns.

DFP and SM images of the optical flat with small step heights are shown in Figures 8-13.

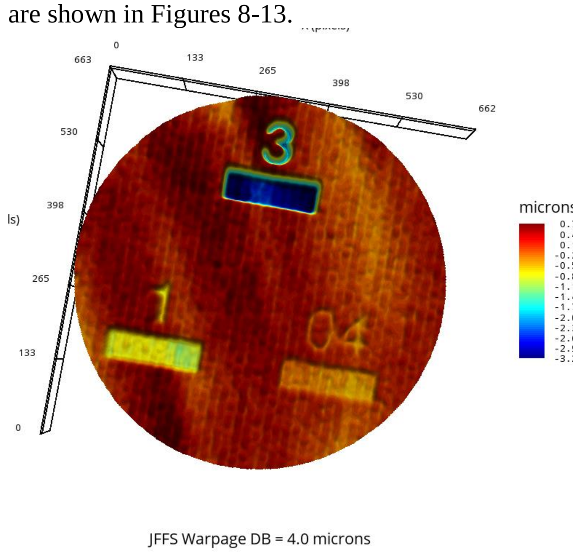

Figure 8. SM, Optical Flat w/ Steps

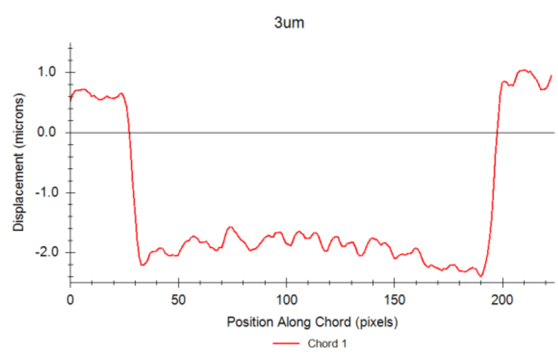

Figure 9. SM, Optical Flat 3um Step, Chord Plot

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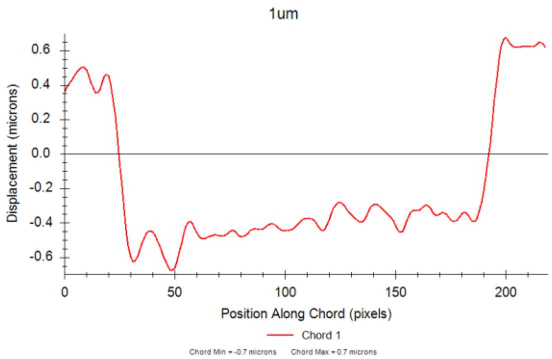

Figure 10. SM, Optical Flat 1um Step, Chord Plot

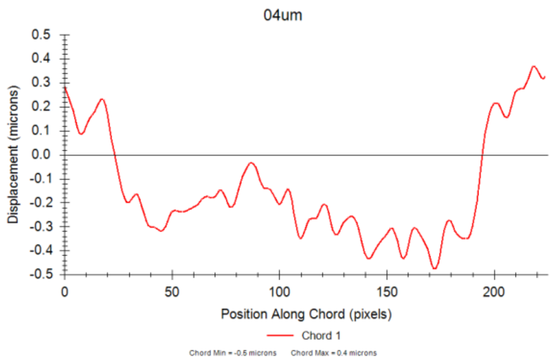

Figure 11. SM, Optical Flat 0.4 Step, Chord Plot

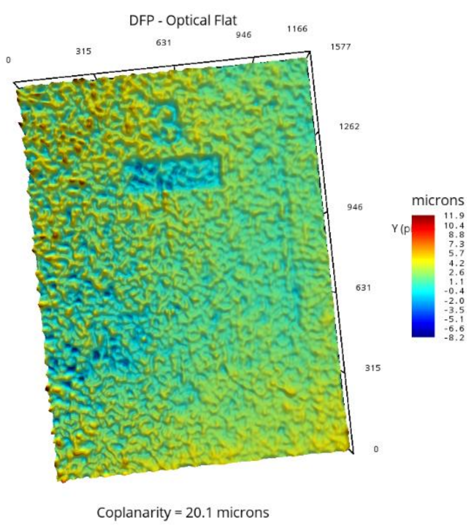

Figure 12. DFP, Optical Flat w/ Steps

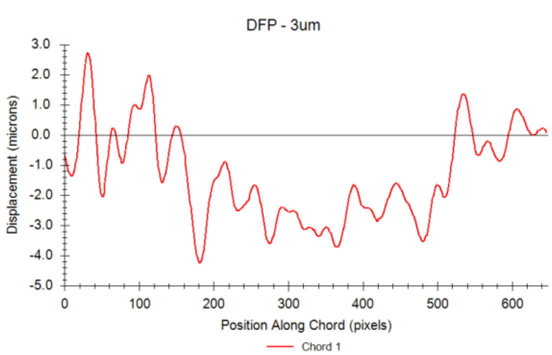

Figure 13. DFP, Optical Flat 3um Step, Chord Plot

*Originally presented at SMTAI 2017.

The SM data suggests the 1.25 micron resolution number is actually fairly conservative, given the detail seen on the 1 and 0.4 micron step. Some sub-micron level of phase shift error can be seen, as expected, in Figure 8, but keep in mind that this is only a 4 micron Z scale in the image. The DFP data at a theoretical 5 micron resolution, can make out the 3 micron step in Figure 12, which suggests that the resolution is perhaps reasonable. However, the step is mostly lost in the noise of the measurement, even after heavier smoothing functions that were applied to Figure 12. Additionally, a coplanarity of 20.1 microns is reported due to the noise in the surface taken across a full field image. This number may be lower on a matte white surface.

Advantage SM. Even with SM setup over a larger area and DFP kept to a fairly small FOV, the Z resolution comparison heavily favors the SM technique for a relatively flat surface. Increasing projector resolution and/or quantities of projectors may narrow this gap.

Sample Preparation

Another point of comparison between the technologies is the need for a diffuse reflective measurement surface. Both technologies rely on light hitting the surface of the sample under test, then reflecting in a diffuse manner back to the camera. Neither technique can measure a purely specular sample nor purely transparent sample. In both cases the ideal surface for optimal measurement resolution is white and matte. Thus a common approach is to coat the sample with a white paint or talc spray. However, the practicality or destructive nature of coating samples is not always desirable. As a point of comparison a single sample was measured with both techniques at room temperature with and without paint. The sample is an unpainted BGA with solder balls removed and has a combination of a common green substrate material and reflective solder ball areas. To make data density fall better in line for comparison the SM data is smoothed with a 5x5 kernel and the DFP data is smoothed with a 17x17 kernel. Results are shown Figures 14-17 and Table 3.

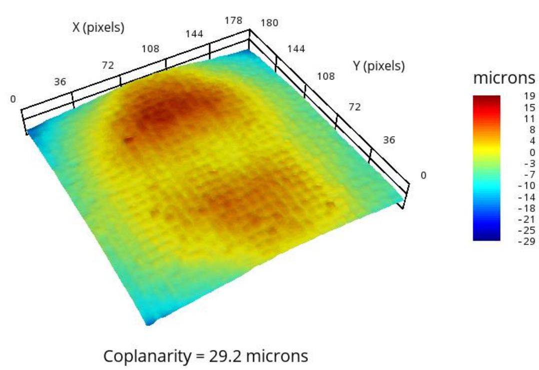

Figure 14. SM, No Paint

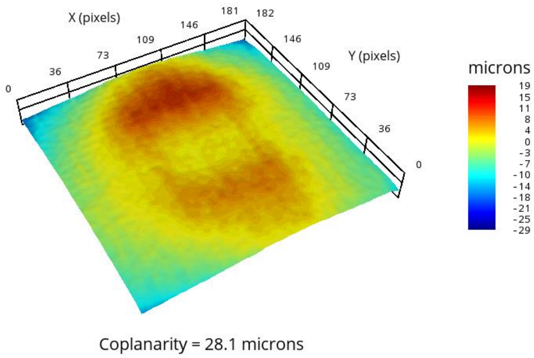

Figure 15. SM, With Paint

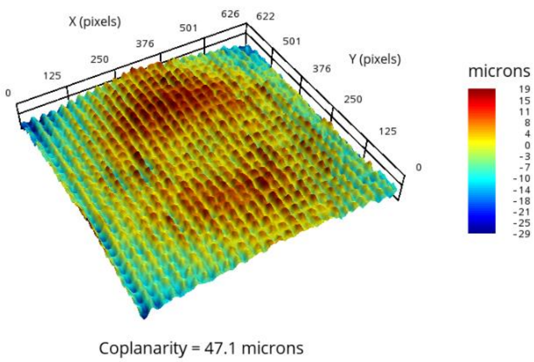

Figure 16. DFP, No Paint

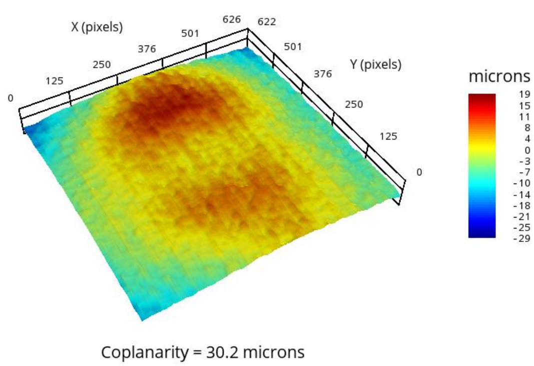

Figure 17. DFP, With Paint

Table 3. Paint Resolution DFP vs SM

Setup	SM No Paint	SM Paint	DFP No Paint	DFP Paint
Warpage	29.2 um	28.1 um	47.1 um	30.2 um

The specular solder ball is causing some error in the unpainted DFP measurement in this case. The left side of the ball has a spike where more light is reflecting directly back to the camera. The rest of the data correlates well and is within expectations for correlation.

Advantage SM, (but…). More development has been but into SM than DFP for the tools used in this comparison. Specifically, the SM data has 12bit grayscale depth and the DFP data has 8bit grayscale depth. Bit depth is covered more in discussions on SM developments. Possibilities of using different image approaches, such as an HDR (High-Dynamic-Range) image, is certainly possible as a compliment to the DFP technology.

Data Density and Data Smoothing

SM has specific limitations with respect to grating pitch in terms of the minimum pixel size, a disadvantage, as discussed early in talking about advantages and disadvantages of the technique. In contrast, with DFP minimum achievable pixel sizes are not as easy to define and will generally be smaller than SM. Limitations to DFP pixel size may come down to practical costs or possible aberrations coming from the observation window in an oven used for measurement over temperature. While examples here only cover a single camera for the DFP technique, scaling up to multiple cameras for DFP measurement is certainly possible. Common examples of pixel sizes between SM and DFP are shown in Table 3.

Table 3. SM vs DFP pixel size examples

Technique	Pixel Size (microns)
SM w/ 50 LPI grating	508x508
SM w/ 100 LPI grating	254x254
SM w/ 200 LPI grating	127x127
SM w/ 300 LPI grating	85x85
SM w/ 500 LPI grating	51x51
DFP at 64x48mm FOV w/ 2MP camera	40x40
DFP at 64x48mm FOV w/ 12MP camera	16x16
DFP at 200x150mm FOV w/ 2MP camera	125x125
DFP at 200x150mm FOV w/ 12MP camera	49x49

Smaller pixel size numbers are advantageous to show more surface detail or measure small features of a sample surface. However, as is seen in the sample preparation study, more data can also lead to more noise. While DFP is almost always taken at higher data density the need for smoothing to compensate for noise in the image can result in comparable or at times even favorable data density for SM. Refer back to the Figure 14 and Figure 17. SM data covers 180x178 pixels with a 5x5 kernel smooth. DFP data covers 626x622 pixels with a 17x17 kernel smooth. The smoothing kernel size was chosen intentionally having a similar ratio between smoothing kernel and data density in order to improve correlation between the techniques. In contrast, Figure 18 shows the DFP data with only a 5x5 kernel smooth. This smaller smooth doesn't show any further surface detail on the relative flat sample, but highlights some of the phase shifting error in the 5 micron resolution technique. While in Figure 14 some of the detail of the remaining solder material on this surface can be seen in the data set.

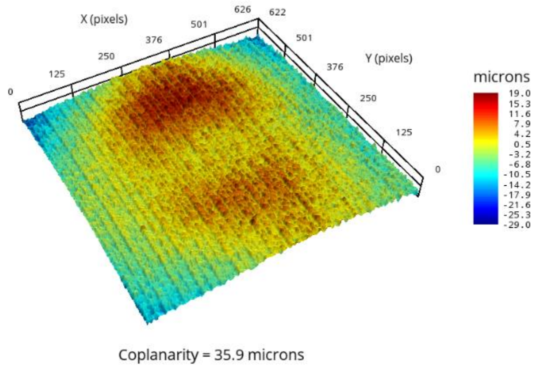

Figure 18. DFP, With Paint, 5x5 Kernel Smooth

Advantage DFP, (but…). The advantage in data density has to go to DFP without a practical limitation to camera resolution and data density. However, the added data density is only beneficial for certain applications, covered further in talking about balled samples, etc.

Throughput

The comparison of SM and DFP would be incomplete without a mention of throughput. Though there can be differences in time to complete a thermal cycle, this only accounts for small differences between the technologies. Additionally, data processing and reporting time would be a variable in this comparison. However, with today's software technology data processing and reporting time can be fast and effective for both technologies. The primary point of comparison between SM and DFP throughput comes down to FOV. Essentially, how many samples can be tested at a single time? Certainly this will vary with part size, but also varies with required resolution. DFP will have worse resolution with greater FOV. If only interested in a single sample DFP and SM throughput can be 1 to 1. However, a review of Table 2 shows that if trying to keep equivalent resolution and testing large quantities of samples the throughput differences can be as high as 100 to 1 or more in favor of SM. Improvements with DFP resolution in relation to FOV would certainly help this throughput comparison, which is touched on further later in this paper.

Advantage SM.

Balled Samples, Sockets, Connectors and Other Applications with Sudden Height Change

The most favorable applications for the DFP technology involve noticeable height changes occurring in a short space. The strength of data density and the weakness of Z-resolution are both favorable for DFP and many samples. For these sample types a comparison with SM is not even feasible, as the SM technique cannot measure these structures. Figure 19 shows a white painted BGA with solder balls measured with the DFP technique. SM would not be able to get useful data from this sample without removing the solder balls from the surface.

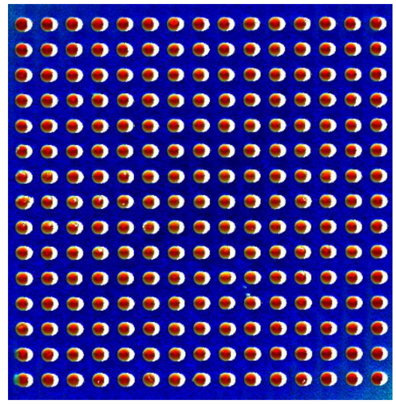

Figure 19. DFP data of balled BGA surface (SM cannot measure these ball heights)

Advantage DFP.

WARPAGE OVER TEMPERATURE CASE STUDY

In order to have a complete comparison between the two technologies a short case study of warpage measurement over temperature is performed. In order to have a fair comparison of the techniques numerous variable are kept as controls. Critical controls and variables for the brief case study are listed below.

Controls:

- Sample precondition: 125°C overnight prebake, then reflowed once prior to any measurement
- Sample coating: white paint
- Temperature profile: Realistic lead free reflow timing and temperature to 250°C max, 9 acquisitions per profile
- Sample: 13x13mm single core BGA, quantity 12
- Sample Support: Quartz Glass, 2mm thick
- Oven: Same oven for all runs, with top and bottom IR heating
- Data Smoothing: 5x5 kernel displacement smooth for SM, 17x17 kernel displacement smooth for DFP

Independent Variables:

- Measurement Technology: SM or DFP
- FOV: 174x120mm for SM, 64x48mm for DFP
- Sample to Sample Warpage Variation

Dependent Variables:

- Sample JEDEC Full Field Signed Warpage, measured over three thermal runs for each technique

Case Study Results:

An example of the surface shape at maximum temperature is shown in Figure 20 as measured by SM and Figure 21 as measured by DFP.

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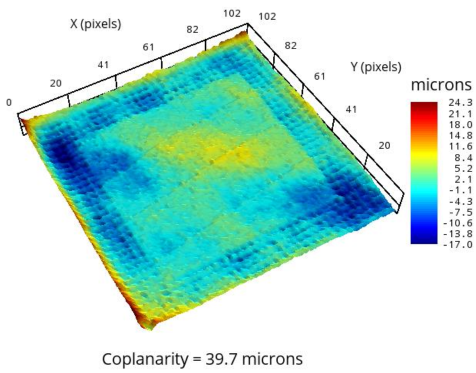

Figure 20. SM, Case Study Sample at 250°C

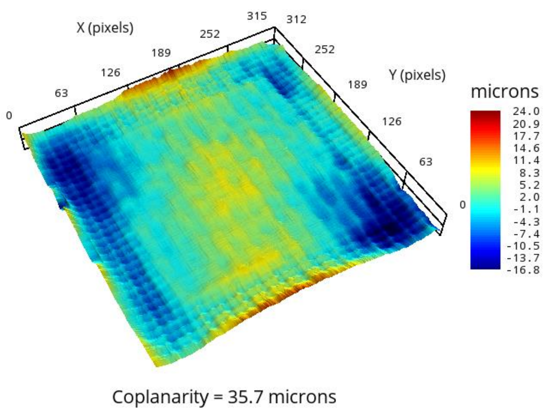

Figure 21. DFP, Case Study Sample at 250°C

Adding the many variables that come into play with thermal testing, the match between DFP and SM is reasonable but qualitatively some differences can be seen.

JEDEC Full Field Signed Warpage is averaged at each temperature point per technique in order to focus the study on comparison of the techniques. Results for SM and DFP are shown in Figures 22 and 23.

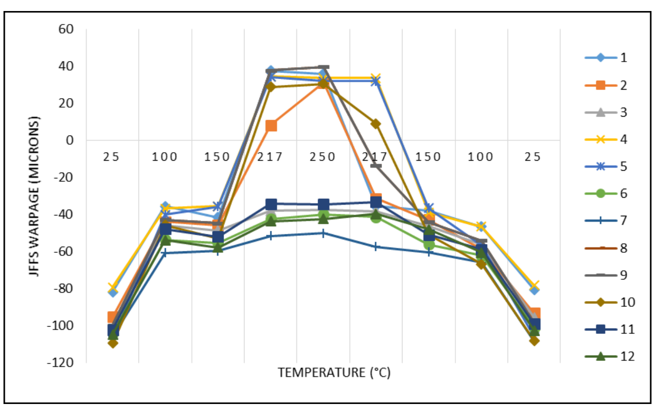

Figure 22. SM, Case Study JFFS Warpage Over Temp.

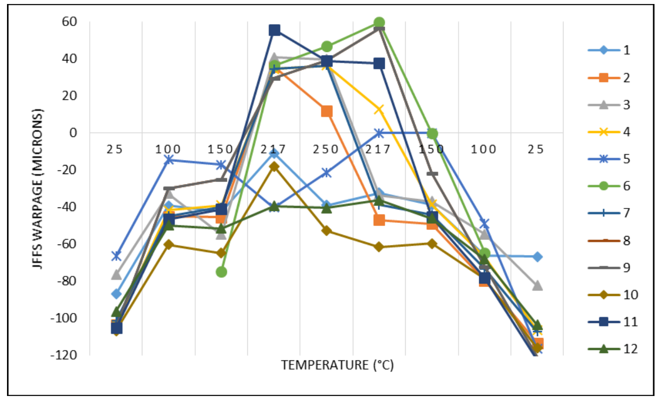

Figure 23. DFP, Case Study JFFS Warpage Over Temp.

The DFP data seems a bit more sporadic. However, the changing from positive to negative of the sign also plays a role in this case. Using signed warpage as a gauge provides more information than coplanarity, but it can also lead to confusion in interpretation of the data. [11] To better correlate the SM and DFP results all parts are averaged together and coplanarity values for SM and DFP for all samples at each temperature are shown in Figure 24.

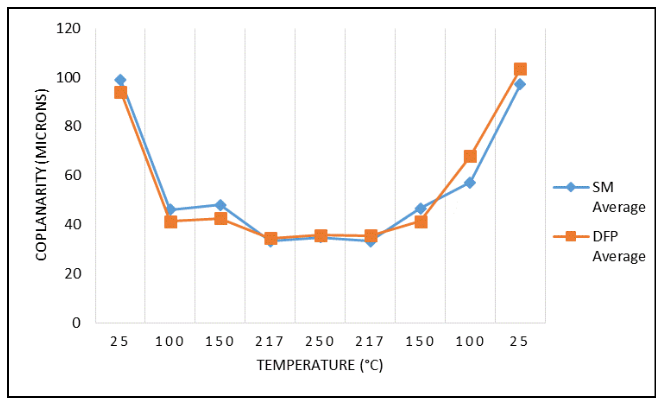

Figure 24. SM vs DFP, Case Study Coplanarity Over Temp.

Figure 24 shows a stronger correlation between DFP and SM over temperature taking out sample variation.

SHADOW MOIRÉ TECHNOLOGY IMPROVEMENTS

Phase Bridging

As discussed, the ability to measure discontinuous surfaces is a significant advantage of using DFP over SM. However, recent improvements in SM software technology have narrowed this gap allowing SM to be used on many discontinuous surface applications. This technology is referred to as phase bridging, discussed in detail in a study focused on measured “Die Tilt”. [12] The phase bridging approach does not provide a solution for all applications. For instance, BGA ball peaks such as in Figure 19 can still only be measured by using DFP technology.

The source of SM’s inability to work with discontinuous surfaces is the loss of what is called Fringe Order. Fringe Order is essentially a count of a number of fringes across the surface. Figure 2 is a common example of an SM pattern where the number of fringes can be counted along a path. However, if we were to remove a portion of the data and create two separate islands of data, as in Figure 25, the beginning and ending of each fringe when crossing this gap is not obvious.

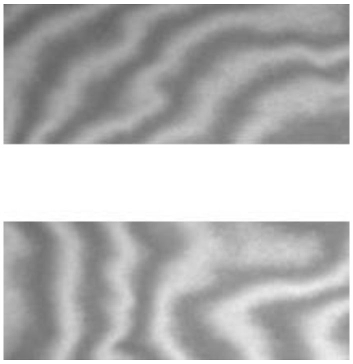

Figure 25. Shadow Moiré Pattern with Missing Data

The phase bridging technology relies on the existence of a common reference plane in the grating glass along with the user's knowledge of the sample dimensions. In order to use this technology the different in surface heights between islands of data only needs to be known within one Fringe Value. For this case of Figure 25 this is 254 microns. 254 microns is a lot of height in the world of microelectronic warpage, so in many applications this approach is viable and in most the "bridge" can be assumed to be zero. To be clear, creating a bridge with a height of 0 does not specifically offset the data by that amount it simply gets it within the 254 micron window and then the algorithms for rotation and phase stepping take over from there. Figure 26 shows the effect of using phase bridging on this sample. This technique doesn't affect the SM accuracy. If the data is incorrect it will be incorrect by 254 microns, or a multiple there of, which for most applications would be very obvious to the user. This approach is rather new at the time of this writing and recently in use in the industry.

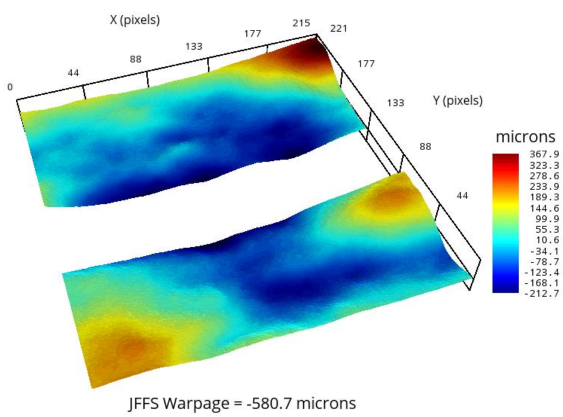

Figure 26. Data Set with Phase Bridging

Temperature Uniformity and Topside Heating

Temperature uniformity during dynamic temperature profiling has always been a critical design point for thermal warpage metrology. Both SM and DFP require a clear path for observation above the sample, which prevents oven design that matches a standard reflow oven. However, SM has a further disadvantage that the grating must also be above the sample and in close proximity. Lateral temperature uniformity across an area faces the same challenges between DFP and SM. The disadvantage of SM is specific to top to bottom temperature uniformity of the sample. Recent technology improvements greatly lessen or even remove the gap of disadvantage for SM and top to bottom uniformity.

An initial advantage to improve top to bottom uniformity is to lower the sample away from the grating during heating and raise closer for measurement. Because SM is typically paired with an accurate vertical motion system and measurement acquisitions are not continuous, implementation of this improvement can be automated. Using a lower while heating function narrows the gap, but further development has been pursued.

Using convection instead of IR radiation allows hot air to pass between the sample and grating. With appropriate design overall temperature uniformity is possible using convection, but current technology can only do this in a limited space. Heating is from the side, since inspection must be from above. Because the heated air will lose energy to the sample, grating, and sample support during travel as this concept increases in scale lateral temperature uniformity becomes as issue. Air flow rates are also limited by the stability of the sample. Thus convective heating can be used with SM for a very uniform heating area, but in practice has only be effectively executed within a 70mm diameter area. A specific approach to this concept can be found within US Patent 9,383,300. While the convection solution fits many common package sizes, the current trend of warpage testing tends toward the need for high volume throughput, which calls for a demand for an evenly heated larger FOV.

The most recent innovation in this area at this time increases usable FOV and maintains temperature uniformity returning to the use of IR radiation heating. In order to optimize top to bottom uniformity a topside heating source is needed. Placing topside heaters between the grating and sample is impractical due to SM working distance constraints. Instead heaters are place above the outer perimeters of the grating and are used to push energy into and through the grating itself. Simply heating the grating directly is helpful to top to bottom uniformity, but in order to optimize the effectiveness of the top heaters as much energy as possible must pass through the grating glass. Figure 27 shows the light transmission curve of the Borofloat material used for the 5mm thick grating glass. [13]

*Originally presented at SMTAI 2017.

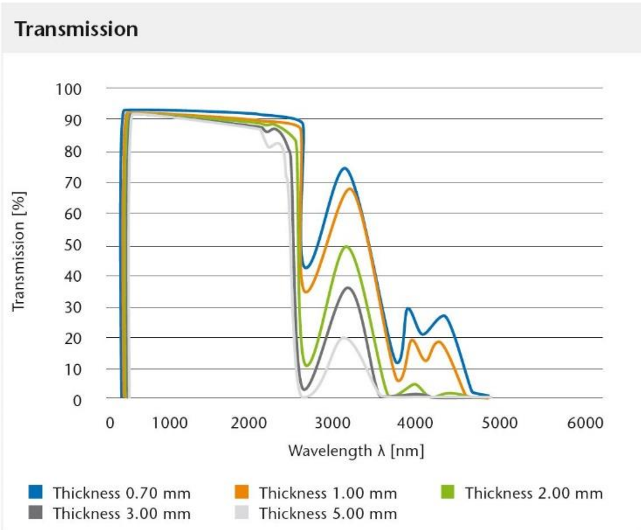

Figure 27 Borofloat Light Transmission [13]

In order to effectively transmit through the Borofloat glass short wave (700-2500nm) IR wavelength are required. This presents a different problem. Heater bulbs can be designed for shorter or longer wavelength but will always produce a range of wavelengths. If trying to use IR bulbs in the short IR range, inherently the bulbs will also produce visible light as well. The visible light will interfere with the SM pattern. Thus in addition to specifically shortwave bulbs, the visible light from the bulb must also be filtered out via dark ruby quartz tubes. This combination of approaches is patent pending and leaves the user with a 300x300mm area that can heated with high uniformity.

8-Bit Vs 12-Bit Data Acquisition

Comparison between SM and DFP with painted and unpainted samples has been previously detailed in the "Sample Preparation" section. It should be noted that the data processed for SM was done with a 12bit gray scale depth and the data processed for DFP was done with 8bit. Increasing bit depth increases the ability to see smaller changes in light. SM made the jump from 8bit to 12bit and saw improvement in the ability to measure unpainted samples. Minimum improvements was seen in optimal sample surfaces. The concept is detailed further in a previously referenced study on "Die Tilt". [12] This study also included the 8bit and 12bit images of a wafer surface, which is highly specular, seen here in Figure 28(a) (b).

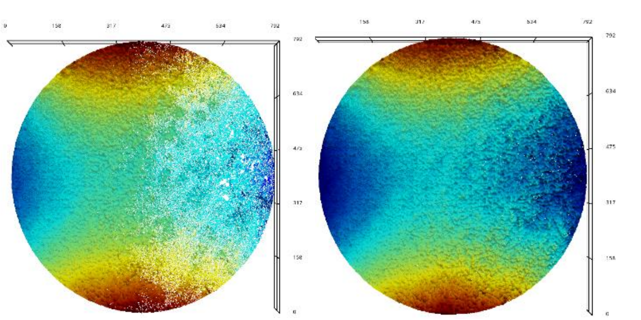

Figure 28 (a) 8 bit measurement **(b)** 12 bit measurement [12]

In theory DFP could be taken with 12bit data processing as well. The improvement that this would or would not have to the technology is not understood by the author at the time of this writing.

DIGITAL FRINGE PROJECTION TECHNOLOGY IMPROVEMENTS AND CONCEPTS

Projector Resolution

Earlier sections have covered how DFP is limited with respect to projected pixels per FOV or projected pixel density. While this relationship remains unchanged, the quantity of projected pixels can certainly change. The limit to projected pixel density comes down to cost, physical space, and possibly acquisition time. Increasing project pixel density can be achieved through:

- Higher resolution projectors
- Multiple projectors
- Scanning projectors

DFP does require very specific optics to handle effects such as nonlinear gamma output, so a change to a higher resolution projector must be done with care. However, conceptually the approach is straight forward. More projected pixels will give better resolution per FOV. The same would be true for multiple projectors working together. In this case space to physically place the projectors themselves could become a limitation. Using DFP with a scanning projector and camera, essentially moving the camera and projector around multiple FOVs, is a common approach in 3D AOI and SPI metrology. The primary downside of scanning across multiple FOVs is acquisition time.

With this concept in mind we can rework Table 2 with a larger quantity of projected pixels. In Table 4 below we use a theoretical setup and an estimate of Z-resolution with a quantity of 6, 4K (4096x2160 pixel), projectors. The practicality in terms of space and cost notwithstanding, this shows the concept that DFP has room for improvement. The resolution in Table 4 is shown capped at 1 micron as other resolution limitations may come into place at higher zoom levels. The Table 4 numbers are both approximate and theoretical within this study.

Table 4. Z-Resolution vs. Field of View with qty. 6, 4k projectors

FOV (mm)	*Theoretical DFP Z-Res w/ 6, 4k projectors (µm)	SM Z-Res (µm)
600x600	7.5	2.5
400x400	5	1.25
250x250	3.125	0.85
100x100	1.25	0.85
50x50	1	0.5
25x25	1	0.5

Acquisition time is paramount for measurement of surface warpage over dynamic temperature change. Most solutions available in the industry today complete acquisition in 1 to 4 seconds. More data can lead to more time required for acquisitions. Additionally, taking the time to scan the surface, as is often done in SPI and 3D AOI tools, would increase the timing required for measurement, likely beyond what is acceptable to the user.

Camera Resolution

Camera resolution is a separate topic from projector resolution, as camera resolution does not affect Z-resolution. Improving camera resolution only provides more data across the surface. The out-of-plane accuracy of each camera pixel is determined by the projector optics. Therefore for many continuous surfaces increasing camera resolution is more likely to hurt then help the measurement by adding more noise to the measurement. However, the strength of DFP is in measuring discontinuous surface, such as the solder ball side of a BGA with solder balls attached as shown previously in Figure 19. In these cases having more data points can be critical.

Measurement acquisition time once again becomes a topic when discussing adding higher resolution or more cameras. These hurdles may lessen as technology of the cameras improves. High speed cameras are already often "Smart" and able to hold many frames in memory instead of having to send out the data and bottleneck the acquisition time.

SUMMARY

Shadow moiré (SM) and Digital Fringe Projection (DFP) are two leading at temperature warpage metrologies that have inherent advantages and disadvantages in comparison to each other. A case study is used to show reasonable correlation between warpage measurements in a typical use case of a BGA sample through a reflow profile. DFP can measure some discontinuous surfaces that SM cannot, although development in SM technology has shortened the list of these surfaces. SM will still give the best resolution and throughput for warpage measurement of continuous surfaces, but DFP technology is expected to gain ground as camera and projector technology improves.

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