

# Projection Moiré vs. Shadow Moiré for Warpage Measurement and Failure Analysis of Advanced Packages

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## ABSTRACT

There are three key industry trends that are driving the need for temperature-dependent warpage measurement: the trend toward finer-pitch devices, the emergence of lead-free processing, and changes in device form factors. Warpage measurement has become a key measurement for analysis; prevention and prediction of interconnect defects and has been employed in failure analysis labs and production sites worldwide.

Over the past decade, the shadow moiré technique has become the method of choice for temperature-dependent warpage measurement. It is estimated that there are over 200 such machines installed worldwide. However, as the above-mentioned industry trends began to emerge, certain limitations of shadow moiré became apparent, such as camera resolution restrictions, schematic limitations on heating/cooling mechanisms, and data processing techniques that can affect accuracy. As a result of recent developments in projection moiré technology, these issues have been addressed, and the technique is poised to meet the future requirements of the microelectronics industry.

In this paper we discuss projection moiré as a new technique for warpage measurement of advance packages, with applications in failure analysis, new product qualification and process control. Projection moiré addresses many shadow moiré limitations, including camera resolution, heating uniformity and noise.

Key words: warpage, failure analysis, interconnect defects, moiré, shadow moiré, projection moiré, coplanarity.

## INTRODUCTION

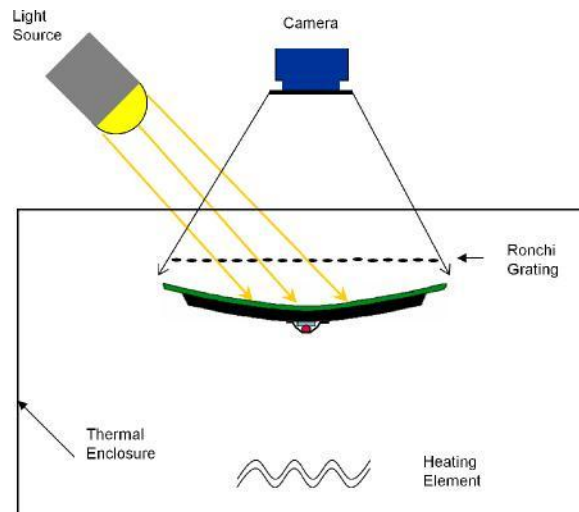
Today developers of ICs are facing reliability demands from customers asking for zero defect quality. Besides increasing costs and efforts to achieve this reliability level, even the classical technologies for reliability assessment are challenged.

The current failure characterization technologies like X-ray imaging or scanning acoustic microscopy all follow a postmortem approach; i.e., they only detect failure modes where the sample is already physically damaged. Thus with decreasing failure probability, a lot of time and effort is wasted in waiting for the manifestation of failures that are supposed to not happen.

Shadow moiré has been used for many years to help predict defects. For example, new designs have been tested for excessive warpage using shadow moiré to determine if the design would result in failures when sent to production. However, while shadow moiré was useful when warpage tolerances were reasonable and parts less complex, the relentless march of advancement in the microelectronics arena has led to the need for a more accurate and reliable simulation of reflow. Projection moiré has shown to meet and exceed these new requirements.

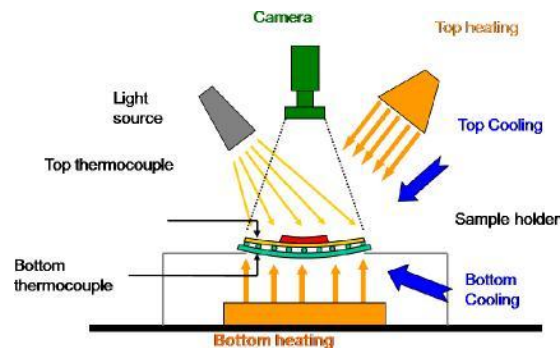
## SHADOW MOIRÉ AND PROJECTION MOIRÉ SETUPS

The basic shadow moiré setup (see Figure 1) includes: a white light source; camera above the sample; infrared heat source under the sample; and a glass Ronchi grating which serves to project the grating lines onto the sample via shadowing. A phase-stepping function is performed by mechanically translating the sample in the z-direction, causing the shadow lines to shift; during this phase stepping, the camera records the line pattern changes, and software algorithms convert these images into 3D computer plots.



**Figure 1.** Schematic of a Shadow Moiré System.

The schematic for projection moiré has some significant differences. Instead of using a glass grating and a white light source to cast lines onto the sample, projection moiré takes a more direct approach: using a digital projector to project the lines onto the sample. Phase stepping occurs by digitally shifting the projected lines via software control. Like shadow moiré, projection moiré typically employs infrared heating; however, because projection moiré does not use a glass grating above the sample, heater elements can be placed above and below the sample for faster, more uniform heating.



**Figure 2.** Schematic of a projection moiré system.

## SIMILARITIES

Shadow and projection moiré have several key similarities that make both metrology techniques quite useful :

1. Data acquisition speed: Both are full-field
2. techniques with acquisition times of a few seconds or less
3. Field of view: Both are scalable, capable of measuring parts up to 400 mm x 400 mm and larger
4. Reflow profiling: Both are capable of being integrated with heating/cooling systems to simulate reflow profiles while measuring warpage in real time
5. Data output: Both can produce 3D plots at various temperature points

## PROJECTION MOIRÉ ADVANTAGES

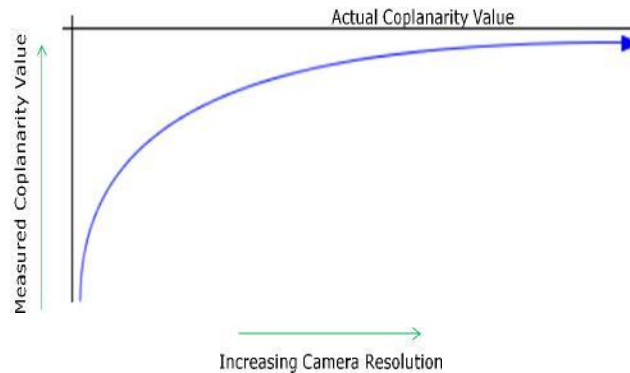
The strengths of projection moiré can be attributed to the following characteristics:

1. No limit to camera resolution
2. More conducive to uniform heating configurations
3. Less noise
4. Capable of measuring non-continuous surfaces

Shadow moiré is limited to low resolution cameras. The technique depends on the creation of an interference pattern between the lines on the Ronchi grating and the shadows projected onto the sample. If higher resolution cameras were employed, the Ronchi lines would be resolved, thus preventing the interference pattern from forming. On the other hand, projection moiré is not limited to low resolution cameras, because it is not dependent on an interference pattern. As a result, camera resolutions are not limited; 5 megapixel cameras are used in today's standard projection moiré systems with fields of view as small as 75 x 75 mm.

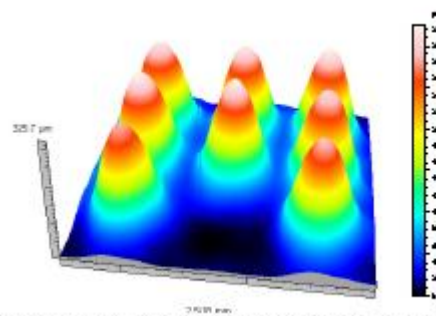
Conversely, the highest resolution camera available with a shadow moiré system is 1.4 megapixels at a field of view of 200 x 200 mm, yielding an effective data density 1/25th of the comparable projection moiré.

Higher camera resolution means more measurement points for a given area. For measurements such as warpage or coplanarity, more measurement points result in more accurate measurements. Also, samples as small as 1 x 1 mm can be measured reliably and accurately as a result of higher data density.



**Figure 3.** General relationship between measured coplanarity and camera resolution.

Perhaps the most important advantage of higher camera resolution is the ability to measure fine surface details. Projection moiré has demonstrated the capability of measuring solder balls/bumps and complex structures such as connectors.



**Figure 4.** Solder ball measurement with projection moiré.

**Figure 4.** Solder ball measurement with projection moiré.

Regarding temperature control for reflow simulation, projection moiré is better suited for uniform heating configurations than shadow moiré. Specifically, projection moiré is not constrained by a Ronchi grating atop the sample (see Figures 2 and 3). As a result, projection moiré systems can have heater banks above and below the sample. More advanced systems employ independent control of the heater banks to further optimize heating uniformity. This creates a more accurate simulation of reflow ovens, and thus warpage behavior in reflow ovens. One-side heating can actually induce more warpage because of temperature differentials throughout the part.

Because the phase stepping exercise in projection moiré is performed digitally by changing the projected pattern, projection moiré has no moving parts. This makes the technique simpler and less costly. On the other hand, shadow moiré requires the use of stepper motors to mechanically translate the sample or grating to create the phase steps. These motors can introduce noise, especially as motors get older and the motion becomes less accurate. Movement of the sample or grating can also introduce vibrations for which there are software compensation techniques.

Finally, shadow moiré is limited to measurement of continuous surfaces. The technique is dependent on continuity of the interference pattern; otherwise the data analysis software will have unwrapping errors. Also, shadow moiré is limited by the use of a single line pattern, the Ronchi grating.

On the other hand, projection moiré is not limited to continuous surfaces because the technique employs the use of 4, 8 or 16 different line patterns, each with different pitches, which allow the software to make gross to fine topographical measurements. This makes measurements such as step heights possible. Additionally, two separate, unconnected surfaces can be related to each other on an absolute basis. As a result, measurements such as lid to substrate tilt, die tilt, package tilt, package heights and other similar measurements are possible with projection moiré.

## **CONCLUSIONS**

Shadow moiré has been the standard technique for warpage measurement in the microelectronics industry for the past 15 years. However, as the industry has progressed, demand for more accurate, more capable techniques has emerged, and projection moiré meets these needs. Projection moiré has the ability to measure warpage more accurately, measure smaller parts and fine features, better simulate reflow conditions, and measure discontinuous surfaces, all with less noise, no moving parts and lower cost.



# **Projection Moiré vs. Shadow Moiré for Warpage Measurement and Failure Analysis of Advanced Packages**

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## Why measure warpage?

### The problem:

Interconnect failures (bridges, shorts, head-in-pillow, etc.) in BGA, CSP, and PoP devices

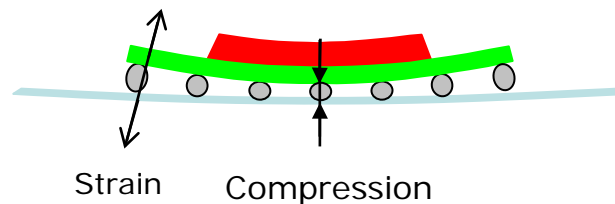
### The cause:

CTE mismatches in the package and/or PCB cause excessive warpage during reflow or thermal cycling

25 C



260 C





## Why measure warpage?

### Industry Trends Driving the Need for Warpage Measurement

- Lead-free solder (higher processing temperatures and more brittle interconnections)
  - Higher density interconnects and smaller solder balls (less tolerance for warpage)
  - Thinner components and PCB (reducing stiffness of parts)
    - Larger BGA-type devices (now 70 mm and larger)





## History of Warpage Measurement

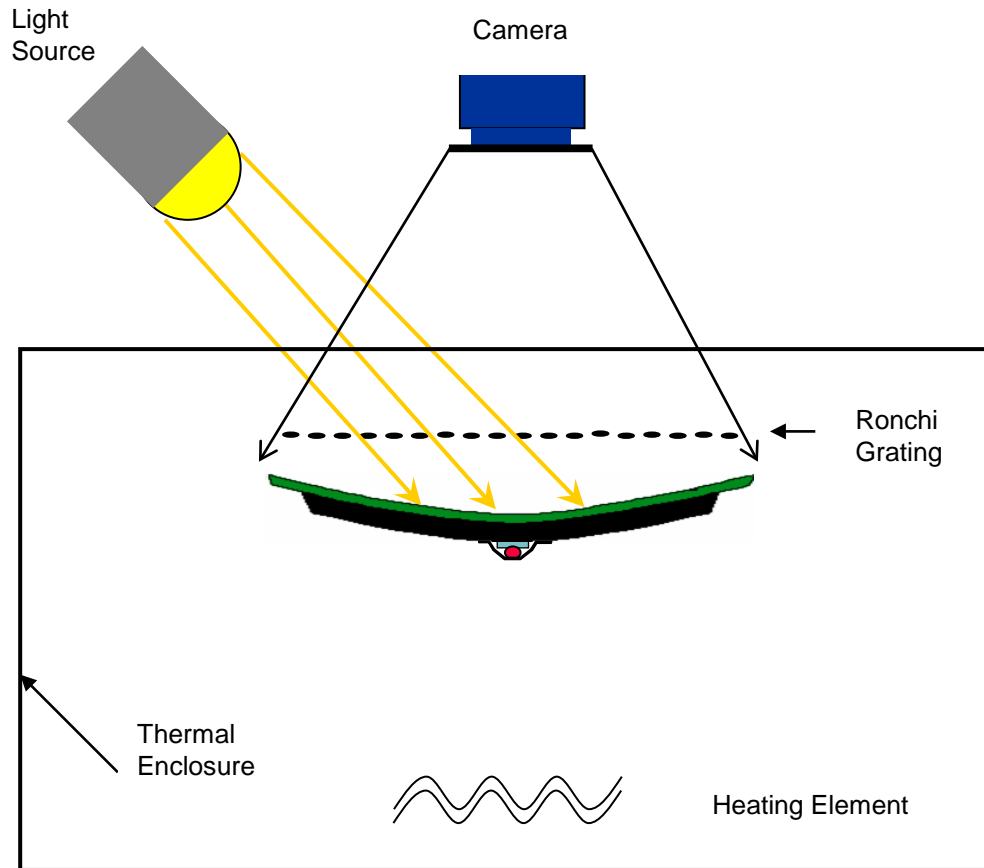
- Early 1990s: Consortium (including IBM, Ford and Motorola) provides initial funding for research to develop a temperature-dependent warpage measurement technique
- Mid 1990s: Research resulted in development of shadow moiré technique
- 1998: First commercial shadow moiré system developed and sold
- 2005: JEDEC Standard 22B112 published ("High Temperature Package Warpage Measurement Methodology")
- 2007: Projection moiré technique independently developed and commercialized by Insidix

*Today, warpage measurement systems have become must-have tools for FA/Reliability labs and manufacturing research labs worldwide, with over 200 systems in the field.*





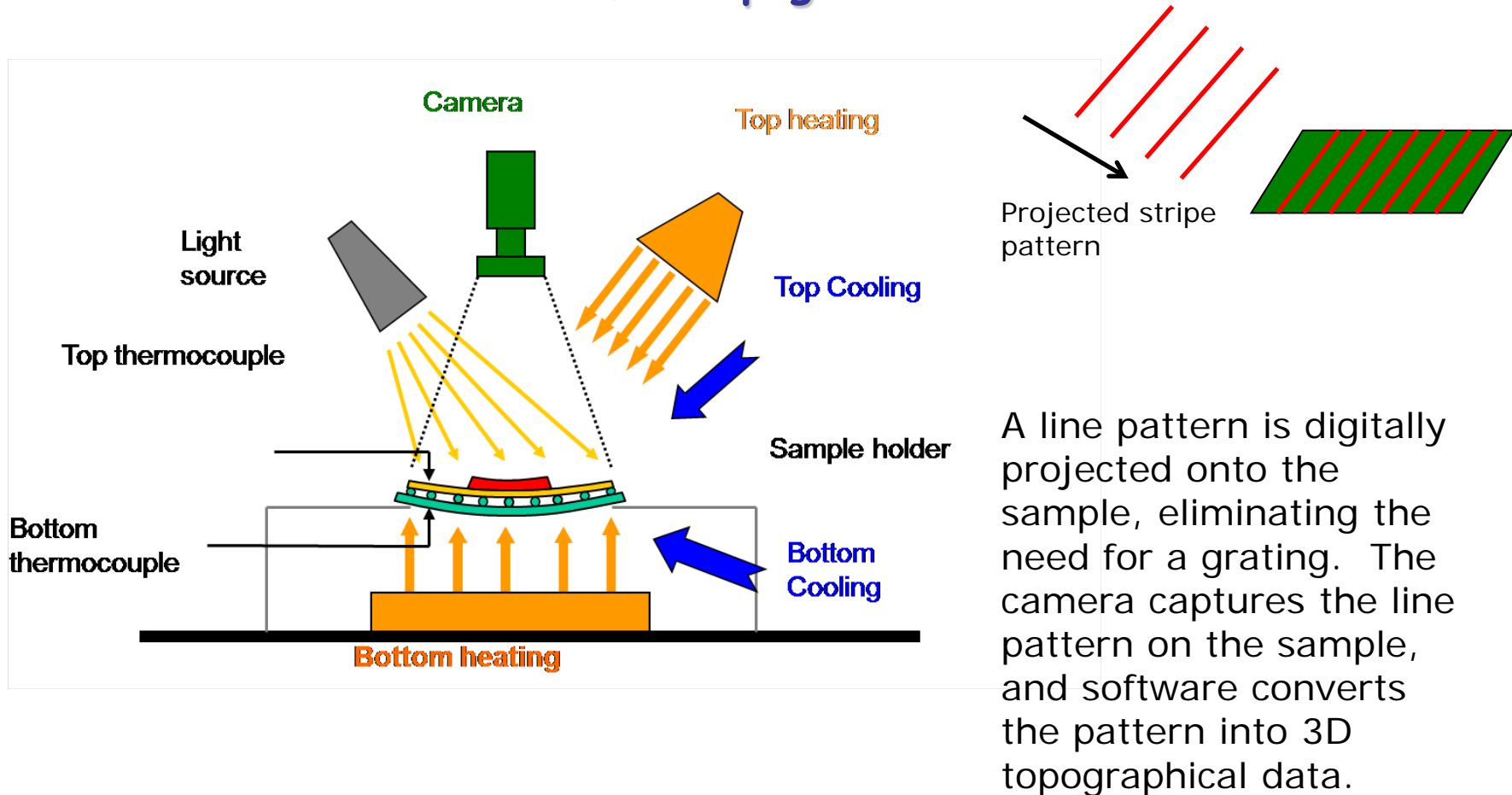
## Shadow Moiré Basics: Legacy Technology



Light is projected through a Ronchi grating, casting shadows of the grating onto the sample. The camera captures the image of the interference pattern created by the grating and the shadow of the grating. Software converts the pattern into 3D topographical data.



## Projection Moiré Basics: The Evolution of Warpage Measurement





## Shadow vs. Projection Moiré

### Similarities Between the Two Techniques

- Data acquisition speed: Both are full-field techniques with acquisition times of a few seconds or less
- Field of view: Both are scalable, capable of measuring parts up to 400 mm x 400 mm and larger
- Reflow profiling: Both are capable of being integrated with heating/cooling systems to simulate reflow profiles while measuring warpage in real time
- Data output: Both can produce 3D plots at various temperature points



## Shadow vs. Projection Moiré

### Projection Moiré Advantage #1: Camera Resolution

- Shadow moiré camera resolution is **limited**; pixel size must be 1.5 times the grating pitch or larger to prevent grating line resolution

In practice, this translates to 0.3 MP camera @ 200 x 150 mm FOV

- Projection moiré camera resolution is **unlimited**

Currently, systems with 4 MP cameras are in production @ 75 x 75 mm FOV

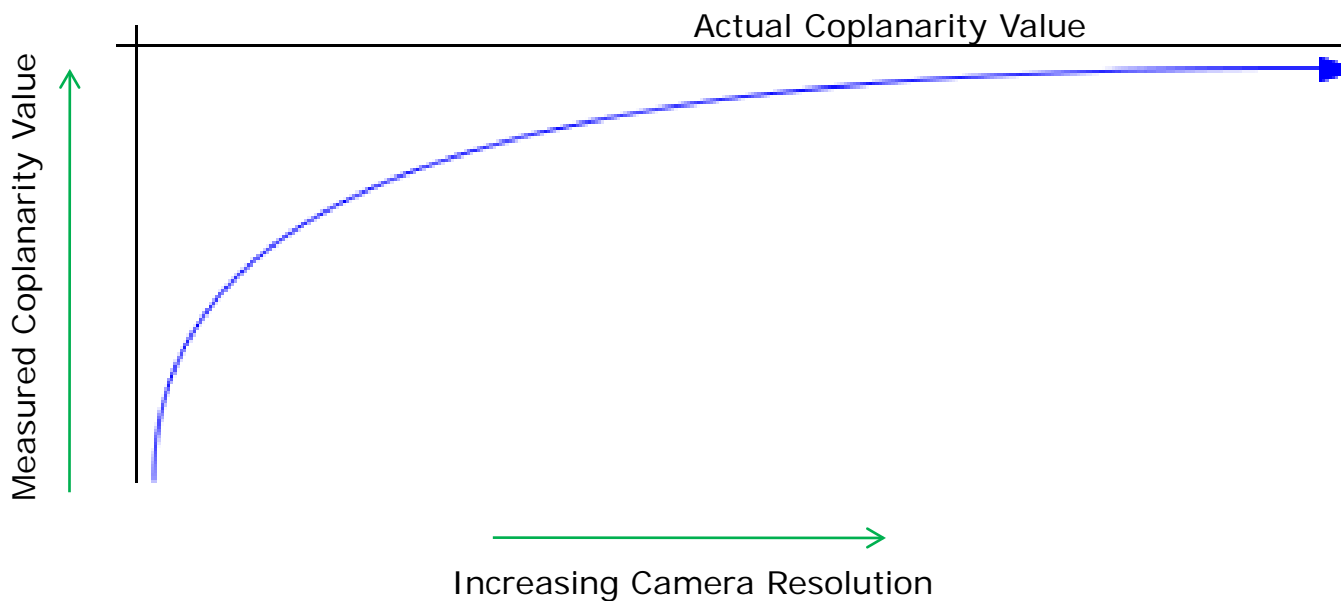
***This translates into ~27x higher pixel density  
by using projection moiré***



## Shadow vs. Projection Moiré

Projection Moiré Advantage #1: Camera Resolution

Higher Camera Resolution = More Accurate Measurements







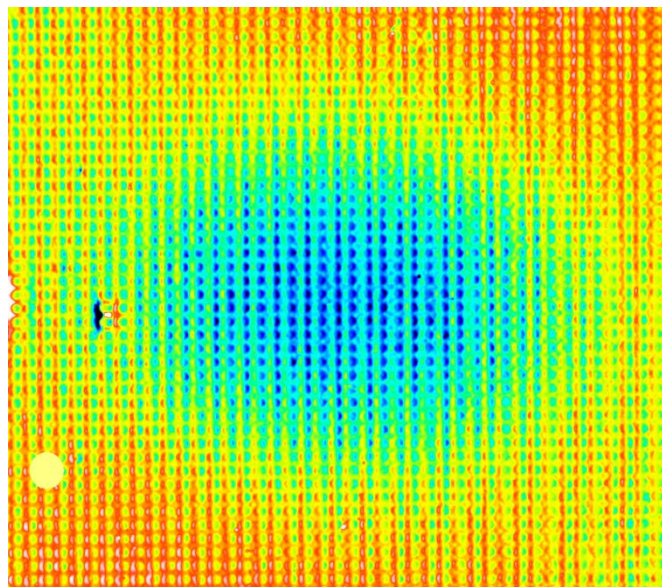
## Shadow vs. Projection Moiré

Projection Moiré Advantage #1: Camera Resolution

Higher Camera Resolution = More Accurate Measurements

High-res camera

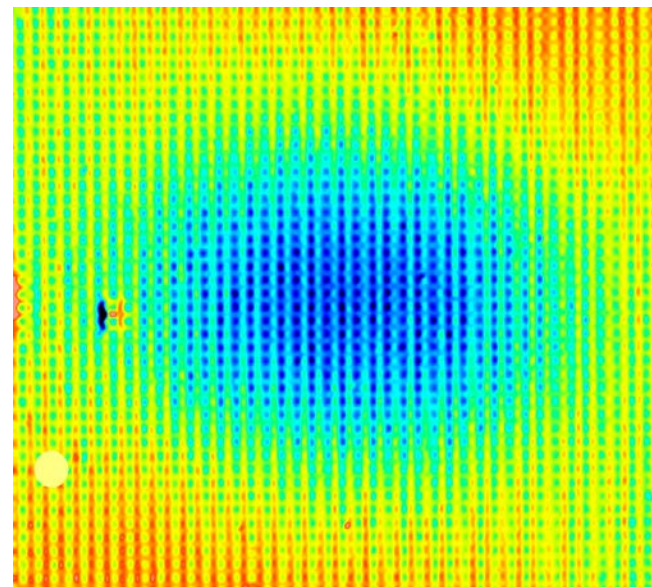
Coplanarity Value: 247 micron



914x821 pixels

Low-res camera

Coplanarity Value: 211 micron



138x138 pixels

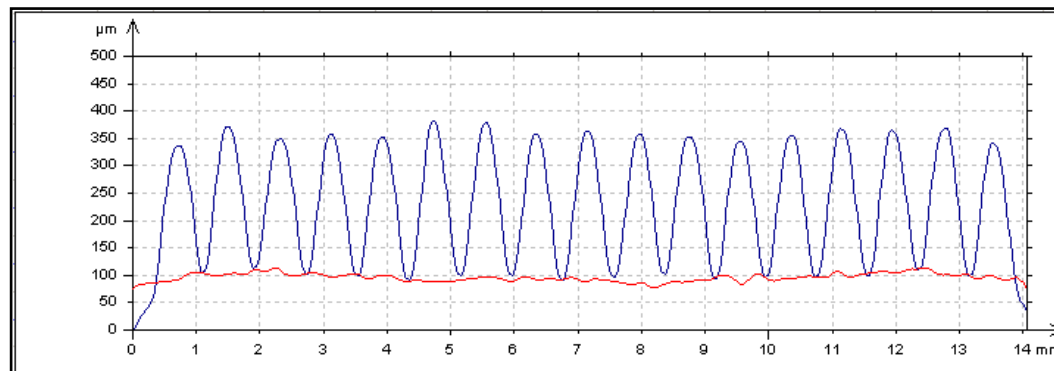
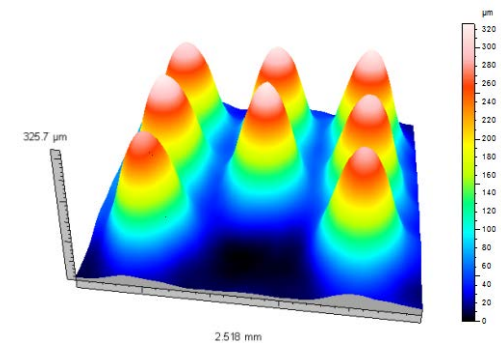
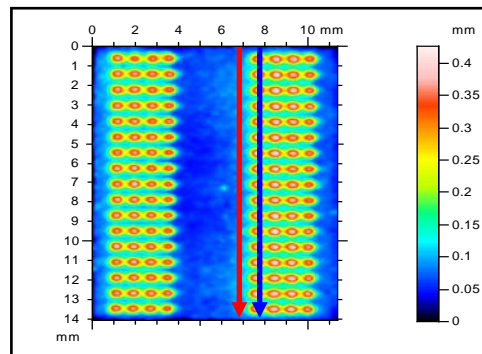
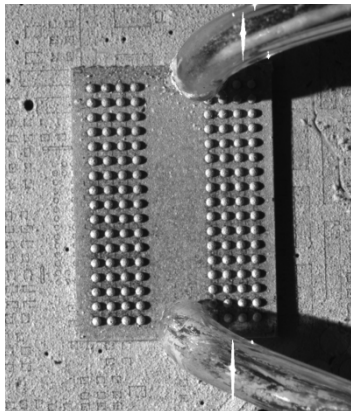
45 mm package, room-temperature measurement



## Shadow vs. Projection Moiré

Projection Moiré Advantage #1: Camera Resolution

Higher Camera Resolution = Fine Detail Analysis







## Shadow vs. Projection Moiré

### Projection Moiré Advantage #2: Heating Performance

- Shadow moiré is **limited** to bottom-side heating due to the requirement of the glass grating to be placed just above the sample

This results in poor temperature uniformity during reflow, especially for thermally massive parts

Glass grating also acts as a heat sink, drawing heat from the top of the part

- Projection moiré does not employ a glass grating; therefore, both top- and bottom-side heating is possible

For even better uniformity, the top- and bottom-side heater banks can be independently controlled

Heating from top and bottom also increases heating rates

***This translates into better simulation of reflow oven conditions***

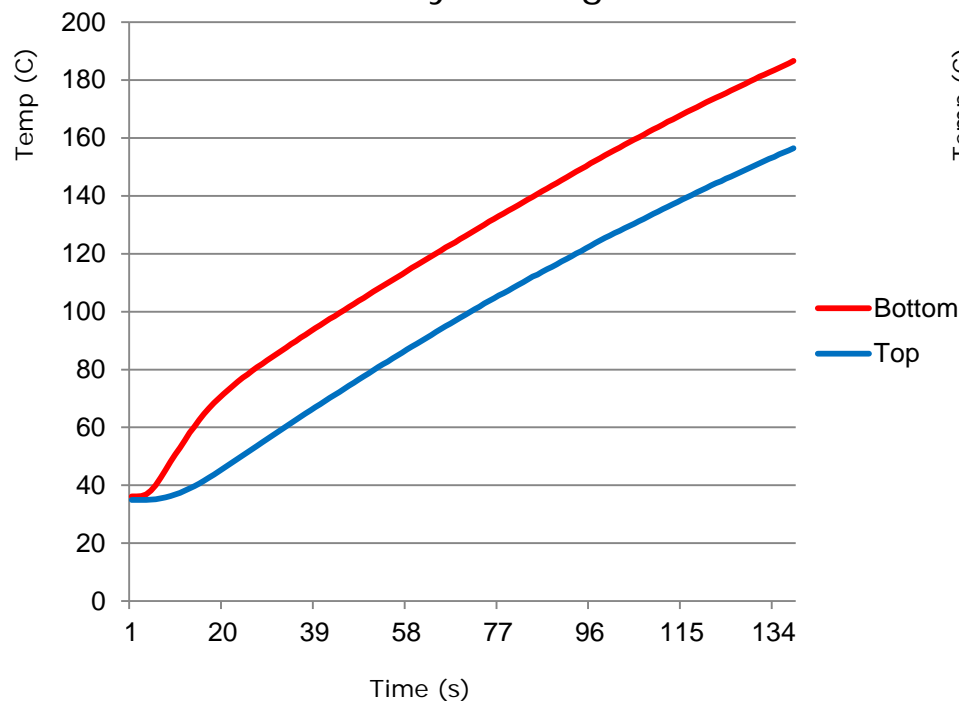


## Shadow vs. Projection Moiré

### Projection Moiré Advantage #2: Heating Performance

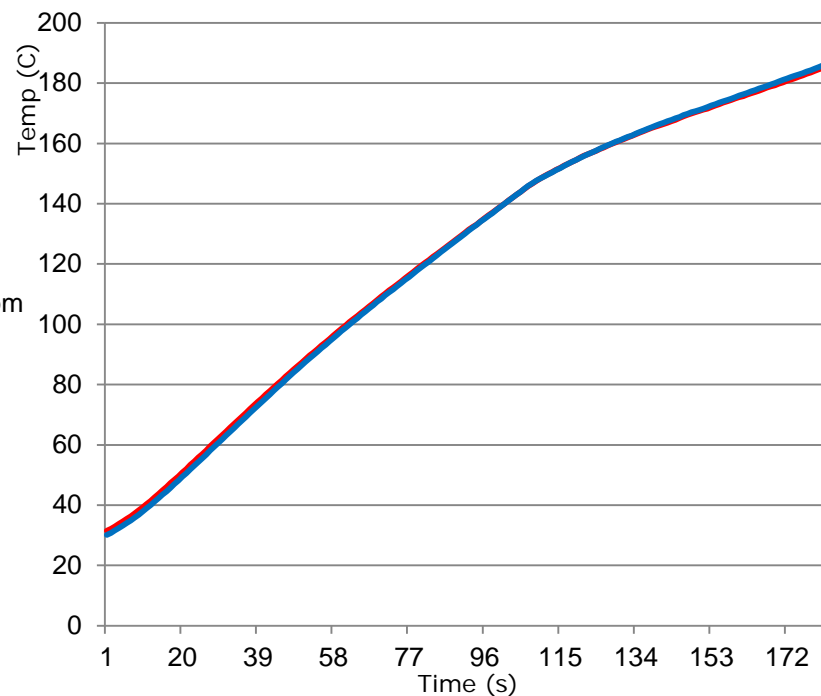
Sample: 45 mm BGA device

Bottom-only heating



**30°C differential at 180°C**

Top & bottom heating



**1°C differential at 180°C**

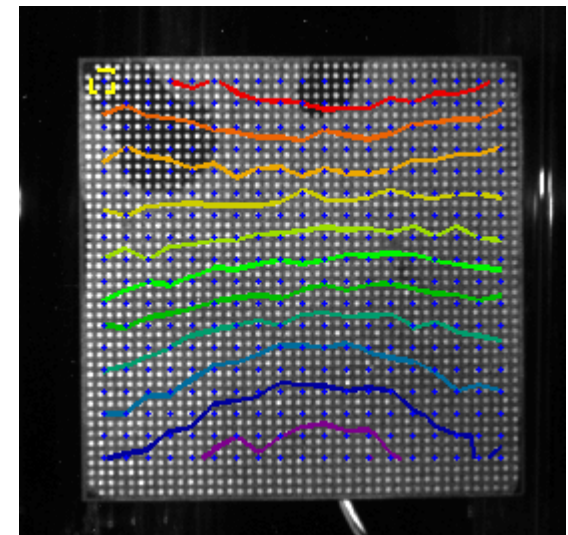


## Shadow vs. Projection Moiré

### Projection Moiré Advantage #2: Heating Performance

How would a temperature differential affect warpage measurement?

- Typical  $CTE_x$  and  $CTE_y$  values for FR4/copper based BGA devices are in the range of  $20 \times 10^{-6}/^{\circ}\text{C}$
- For a 45 mm device and a  $30^{\circ}\text{C}$  differential, this translates to 27 microns of deformation in the x and y directions
- ***With bottom-only heating, the bottom side will expand in the x and y directions significantly more than the top, resulting in convex forces that will affect warpage values***



CTE deformation plot showing y-direction isobars on 45 mm BGA



## Shadow vs. Projection Moiré

### Projection Moiré Advantage #3: Less Noisy Technique

Shadow Moiré employs mechanical movement of the sample to perform the phase shifting of the fringes

- Accuracy and repeatability of the mechanical motion is can be a source of error/noise
- Vibration of the sample is possible during the mechanical shifting, also introducing potential error

***Projection Moiré does not employ any mechanical movement: phase shifting is performed digitally by the light projector***



## Shadow vs. Projection Moiré

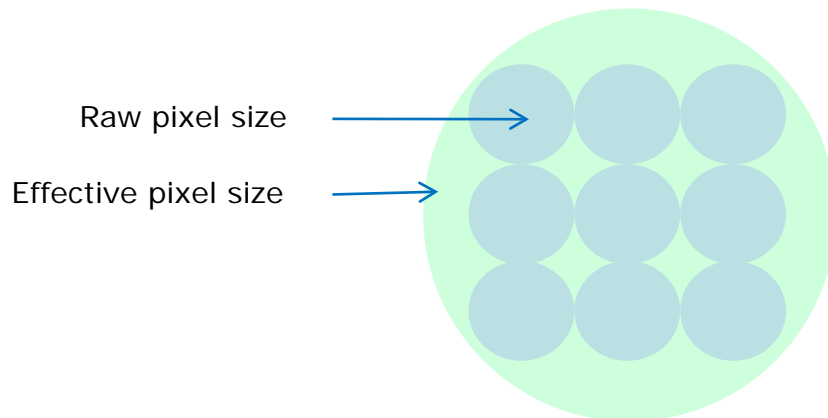
### Projection Moiré Advantage #3: Less Noisy Technique

How does noise affect warpage measurement values?

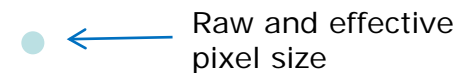
- Shadow moiré typically requires data averaging to minimize noise, typically a 3x3 window pixel averaging technique
- This type of data processing has the same effect as lowering the camera resolution: it reduces warpage values and washes out fine details

***Projection moiré does not require data averaging for noise reduction***

Shadow Moiré



Projection Moiré





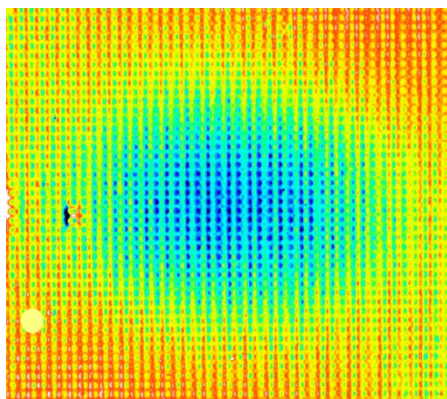


## Shadow vs. Projection Moiré

### Projection Moiré Advantage #3: Less Noisy Technique

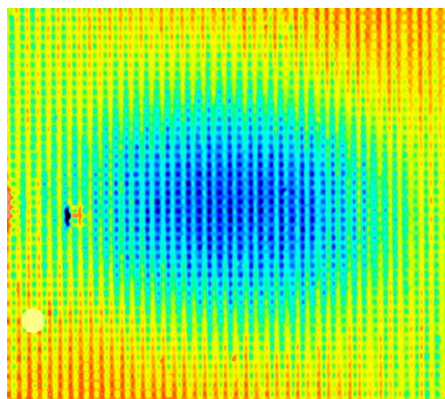
High-res camera

Coplanarity Value: 247 micron



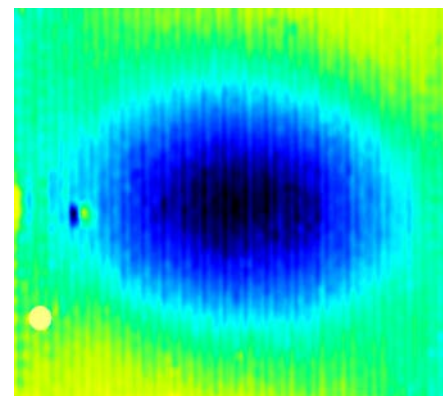
Low-res camera

Coplanarity Value: 211 micron



Low-res camera *and* 3x3  
window pixel averaging

Coplanarity Value: 144 micron



Coplanarity values are dramatically affected by camera resolution and pixel averaging.



## Shadow vs. Projection Moiré

### Projection Moiré Advantage #4: Step Height Measurement

Shadow Moiré uses a grating with a fixed line pitch for shadowing onto the sample

- The pitch (or frequency) of the lines cannot be changed during measurement
- As a result, step heights cannot be measured, and surfaces must be continuous

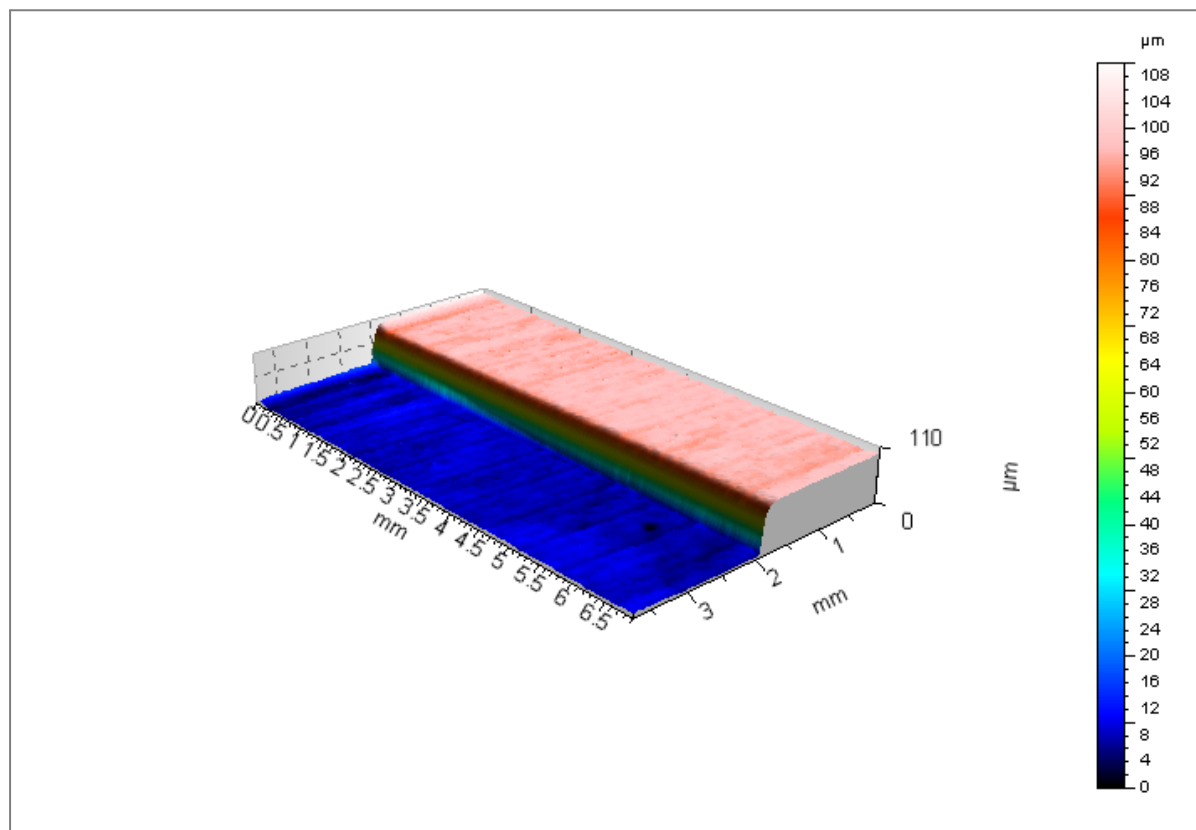
***Projection Moiré allows for the pitch of the projected lines to be varied during measurement. Line patterns with up to 8 different pitches can be projected, allowing for absolute height, step height, and even tilt measurements on both continuous and discontinuous surfaces.***





## Shadow vs. Projection Moiré

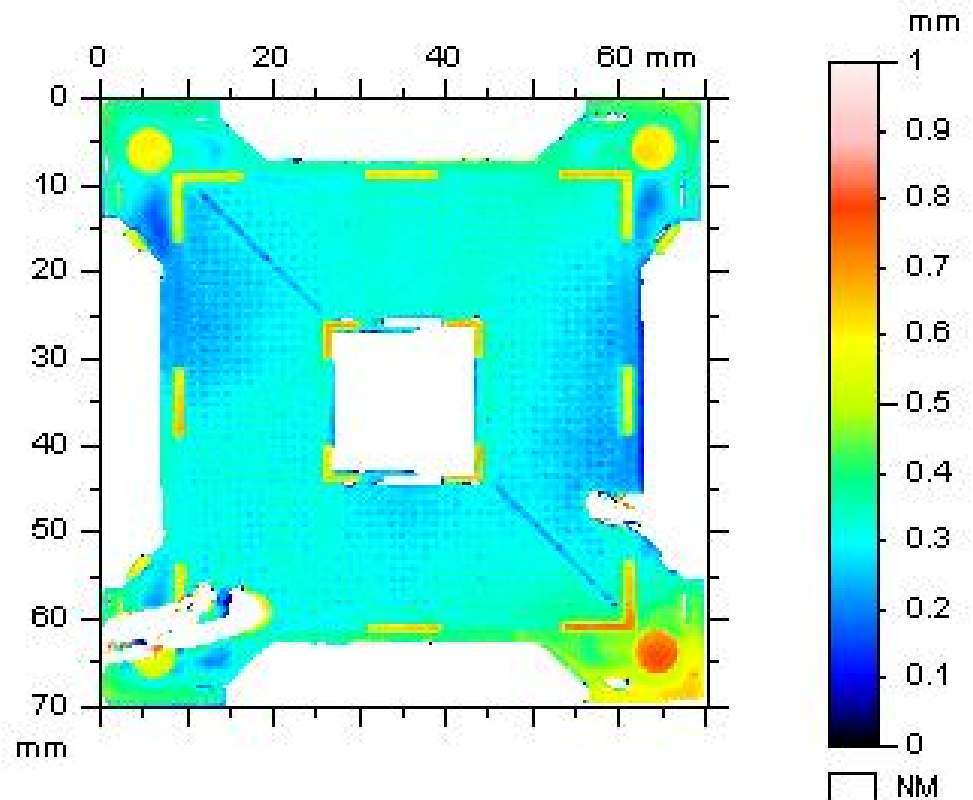
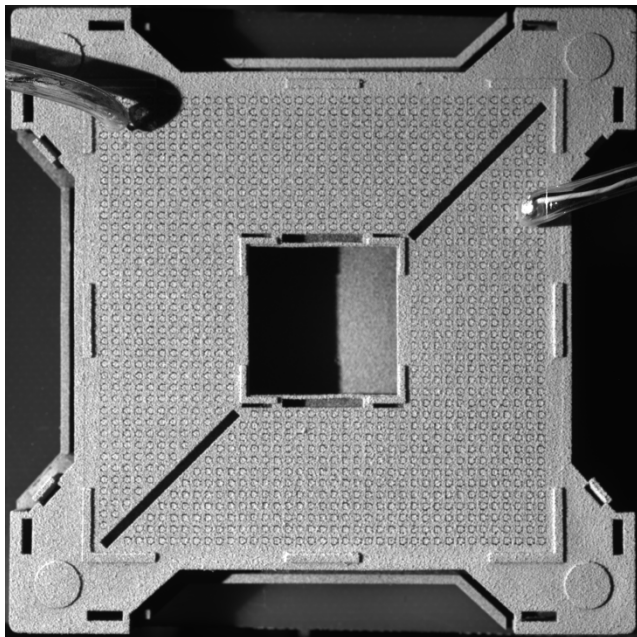
Projection Moiré Advantage #4: Step Height Measurement





## Shadow vs. Projection Moiré

Projection Moiré Advantage #4: Discontinuous Surface Measurement





## Shadow vs. Projection Moiré

### Summary of Projection Moiré Advantages

Projection Moiré is a superior technique for temperature-dependent warpage measurement:

- Allows for higher camera resolution, leading to more accurate coplanarity values and ability to measure finer features
- Allows for more flexible heating setups such as top and bottom IR heating for faster, more uniform heating
- Is a less noisy technique, thus requiring less data processing (specifically, pixel averaging)
- Is capable of measuring step heights, tilt, absolute heights and discontinuous surfaces