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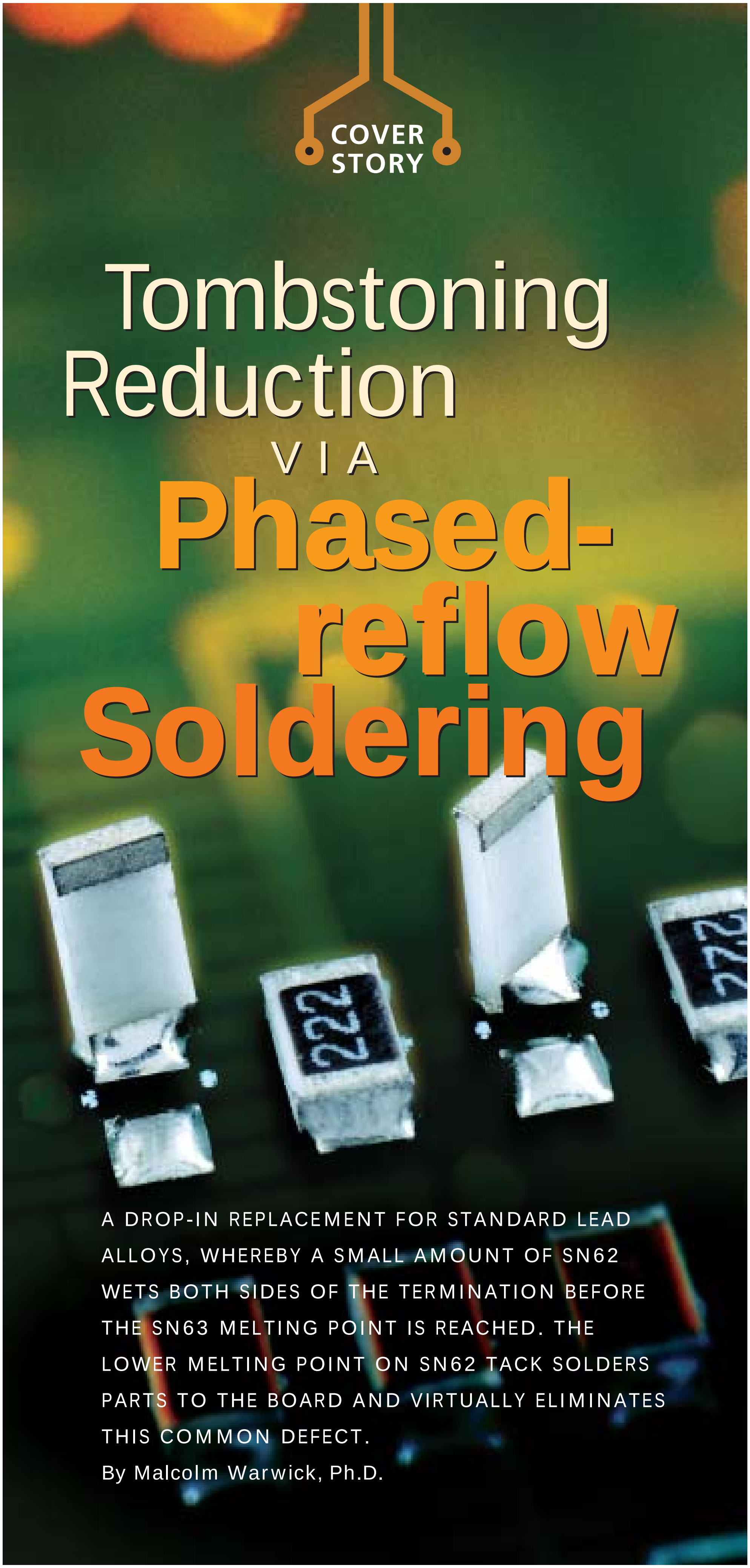
Advantages of Phased-reflow Solder

COVER STORY

Tombstoning Reduction VIA Phased-reflow Soldering

A DROP-IN REPLACEMENT FOR STANDARD LEAD ALLOYS, WHEREBY A SMALL AMOUNT OF SN62 WETS BOTH SIDES OF THE TERMINATION BEFORE THE SN63 MELTING POINT IS REACHED. THE LOWER MELTING POINT ON SN62 TACK SOLDERS PARTS TO THE BOARD AND VIRTUALLY ELIMINATES THIS COMMON DEFECT.

By Malcolm Warwick, Ph.D.



In its most extreme form, "tombstoning" occurs when a component during soldering is raised on one end so that its axis, which should be parallel to the printed circuit board (PCB) surface, is perpendicular, effectively removing the chip from the circuit. In less extreme forms, the component may undergo partial lifting at one end so that electrical contact with one pad is incomplete. In many ways, the latter is a more insidious defect than full-component lifting because it is more difficult to find via visual inspection. Partial lifting may be accompanied by lateral movement, which may make the defect more visible.

Mechanisms Leading to Tombstoning

The primary cause of tombstone defects is the presence of unbalanced forces acting on the component arising from surface tension of the molten solder alloy. To understand the origin of tombstoning, it is necessary to consider all process and material factors. Figure 1 shows the forces acting on a component when it is in contact with molten solder during the reflow process. Analysis shows that the surface tension of the solder will produce a turning moment; thus, it is easy to demonstrate the conditions under which surface tension will be large enough to lift a component, i.e., tilting will occur if: $F_1 + F_2 < F_3$. This translates to:

1. F_1 + the vertical component of surface-tension force acting under the chip is less than the vertical component of surface tension force acting on the top of the chip.
2. Using the symbols in Figure 1, where the mass of the chip is M and g is the acceleration due to gravity, the expression becomes:

$$M.g.\{(D^2 + L^2)/2\}.\cos(\alpha + \theta) + \gamma.W.\cos(\alpha/2) < \gamma.D.\sin(\alpha + \phi).$$

For larger components, the forces are closely balanced and lifting is not certain even when only one end of the component is wetted. In normal circumstances where both ends of the component will be subject to the same forces working in the opposite direction, no undesirable movement will take place. However, once lifting starts, the forces that cause the tombstoning effect will increase.

Vulnerable Components

Several physical factors can increase the risk of incurring tombstone defects, including higher surface-tension forces and lower component masses. It is clear from practical experience that smaller passive devices are more vulnerable. Longer pad extensions, i.e., those beyond the component, will increase the turning moment acting on the device by prompting the solder to fully wet

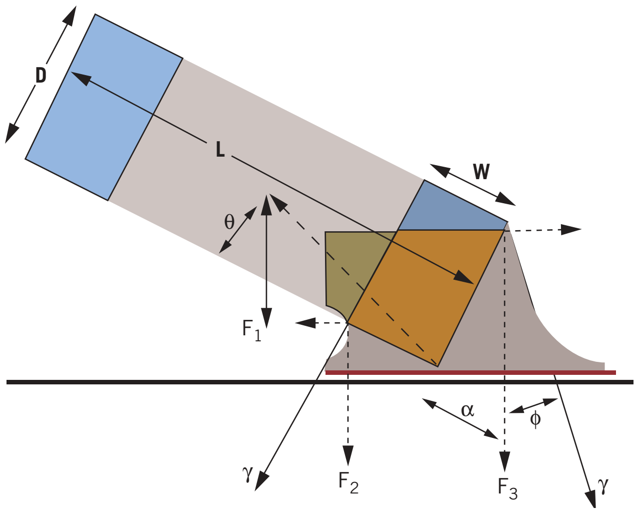


Figure 1. Schematic representation of the forces acting on a chip as it tombstones. Tilting will occur if $F_1 + F_2 < F_3$.

out and reduce the contact angle on the component's termination. However, by increasing the contact area between the PCB pad and the underside of the component, the defect's incidence is reduced by a simple leverage effect. Combining these simple factors shows that the pad design and component placement can influence a predisposition to tombstone defects.

While a misplaced component may experience a greater turning moment at one end, the difference typically is not large enough to break the strong forces exerted by the molten solder in the capillary space under the component. The component will only lift if one end is not experiencing strong wetting forces when the other is feeling the full force of the molten solder's surface tension. The main driving force controlling tombstoning defects is the relative speed of the solder's wetting action at each end of the component. Hence, when the speeds are closely matched, the component remains in place; when they are not, it may move out of position.

Solderability Vs. Wetting Speed

Several factors can influence wetting speed. The most obvious is the solderability of each of the component's terminations. If, however, solderability varies, wetting will occur at different rates. Experimental work using a variety of laboratory test methods, including the wetting balance, has shown that as solderability deteriorates, the range of wetting speeds within a component population increases, i.e., components with poorer solderability will show greater susceptibility for tombstoning.

Stronger fluxes tend to increase wetting speeds and reduce differences in solderability between terminations. They also can increase the extent of wetting, reducing the contact angle and increasing the component's turning moment. Stronger fluxes may reduce or increase sensitivity to tombstoning, which explains some of the contradictory advice for overcoming defects.

The rate of wetting also increases significantly as surfaces get hotter. If one termination is much hotter than the other, the solder alloy may have melted and wet it before the alloy at the other end has even melted. If the different ends of the component are at different temperatures, the molten solder will wet them at different rates and tombstoning may result. Modern convection ovens minimize temperature gradients on a PCB, but design-related factors such as shielding and heat sinking can contribute to a temperature differential. Similarly, changing the reflow profile can change the incidence of tombstoning by affecting both the flux activity and the creation of temperature gradients. Yet, in some cases, increasing preheat time/temperature (reducing flux activity and temperature gradients) may improve results while in other cases, speeding up the profile (maintaining flux activity) will bring about improvement.

Reduced Tombstoning Strategies

Analysis of the root causes of tombstoning indicates that good PCB design, controlled component placement, good component solderability and the "right" reflow profile all are effective in reducing the incidence of tombstone defects. Various strategies have been adopted to make the board assembly process more robust against these defects, focusing attention on the solder paste design.

In one strategy, solder paste designers have selected products with different levels of flux activity. In some cases, a more active flux will reduce tombstoning; in others, it will increase its occurrence. However, changing any of the process parameters (or board design) could then reverse the improvement. For these reasons, solder paste manufacturers have concentrated on a second design strategy with a view toward controlling the rate of solder wetting on each termination of a component by altering the properties of the alloy.

Normal reflow soldering processes use a eutectic alloy, whether binary tin/lead (Sn63) or ternary tin/lead/silver (Sn62). When these alloys reach their melting temperature, they instantly become low-viscosity fluids and begin to wet any clean (fluxed) metal surface in contact. They flow easily over the wettable surfaces, limited only by the flux's ability to keep all the reacting surfaces free from oxidation. If wetting could occur more slowly, however, the molten solder could hold both ends of the component before surface tension exerts the maximum turning moment at one end. This can be achieved if the molten alloy remains viscous for a period after liquidus, which is the case for alloys that show a "pasty" range.

Solder pastes made from noneutectic alloy powders combat tombstoning defects and most commonly include the elements tin, lead and bismuth. This is because that combination has a sufficiently large melting range to produce the desired effect. Typically, because these pastes contain only a low percent of bismuth, the liquid phase volume remains low until close to the liquidus temperature. Other pastes use a mixture of two alloy powders, e.g., tin/lead and tin/bismuth, to achieve the same effect. In this case, the lower-melting alloy flows first and wets the component, board and remaining powder. Mutual dissolution between the powders takes place until forming a homogeneous composition before solidifying at the end of the reflow process. After the joint formation, reliability may be compromised under aggressive temperature-cycling conditions because some of the alloy will remelt at elevated temperatures.

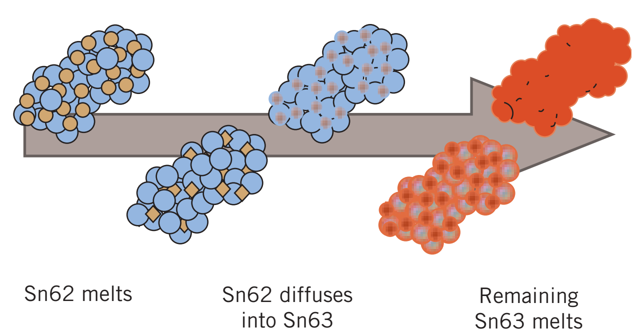


Figure 2. Schematic of the phased reflow of mixed Sn62 and Sn63 alloy powders in solder paste. By using smaller particles in the low melting point solder alloy, the area of contact with the larger (high melting) particles is restricted.

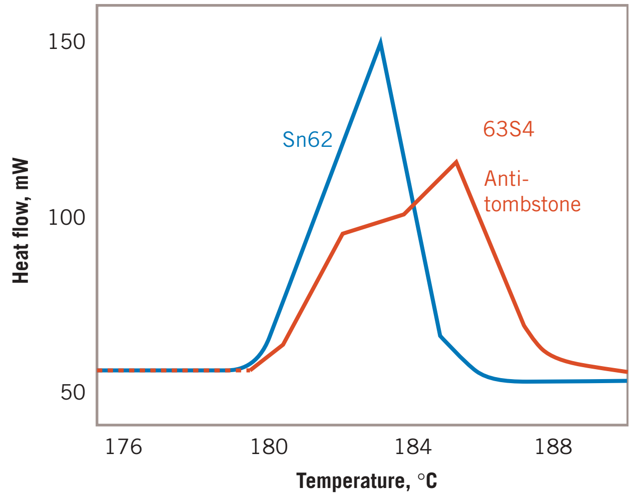


Figure 3. Differential scanning calorimetry for two solder pastes passing through the melting stage in a typical reflow process temperature profile. The X-axis also is a time axis, demonstrating how the extra period in a pasty condition assists in preventing tombstoning during reflow.

Special Paste Formulas

Solder formulators are challenged to create the same effective pasty range without compromising joint reliability. Using a mixture of eutectic alloy powders with nearly the same melting temperature achieves this objective if a lower melting temperature ternary composition is not formed on melting. This is the case if the tin/lead and tin/lead/silver eutectic alloys are used with their melting points of 183° and 179°C, respectively. Reason: When they coalesce, the melting range of the final alloy is only 179° to 183°C.

Attempts to keep the liquid metal volume to a minimum before complete reflow by using a mixture that contains more of the high melting temperature powder are only partially successful. As the lower melting temperature alloy flows, it diffuses into the higher melting particles and creates significantly more liquid too quickly by reducing the entire system's melting temperature. This effect may be reduced by using smaller particles of the low melting alloy, thereby restricting the area of contact with the larger, higher melting particles. This is the concept behind phased-reflow solder pastes whose progress of reflow is illustrated in Figure 2.

Figure 3 is a plot of heat flow in solder paste as it passes through the melting stage in a typical solder paste reflow profile. The heat flow corresponds to the latent melting heat of the solder powder (Y-axis). The X-axis, showing the temperature of the material, also is a time axis as the solder paste passes through the reflow oven. The eutectic solder paste (Sn62) takes a finite time to melt because the system is changing too fast for equilibrium to be established. Nevertheless, it changes from totally solid to totally liquid in a shorter time than the mixed solder powder anti-tombstone blend (63S4). This extra time gained in a pasty condition prevents tombstone defects that otherwise would occur with the eutectic solder paste.

Whatever the theory behind the reflow behavior of the material, the important observation is that it has the desired effect. The data in the table are an example of the laboratory studies that show the clear benefits. The paste is printed onto a standard test board through a 125 µm thick stencil and reflow is performed in nitrogen to increase the defect rate. Generally, such a small sample size would not detect defects at the level seen in most real processes. In real situations at many different customer locations, tombstoning rates have fallen to 0 to 20 percent of their original level.

TABLE

Comparative Defect Data*

Solder Powder Size	# Boards	# Parts	# Defects
Type 3 Sn62 alloy	5	135	15
Anti-tombstone blend	5	135	1

*On tombstoning of 0402 chip capacitors reflowed in nitrogen.

Using a Powder Blend

An inherent property of the alloy powder blend is that the composition of the finished solder joint will not be one of the normal eutectic alloys such as Sn62 or Sn63. Using a powder blend that results in a joint alloy with a long pasty range is likely to compromise strength and fatigue behavior under high-temperature conditions. The pasty range for the phased reflow blend of Sn62 and Sn63 is only 4°C, however, it poses no reliability issues. For all practical purposes, the alloy in the joint displays the same fatigue properties as Sn62 and Sn63, which are interchangeable effectively despite bulk property differences.

The anti-tombstone alloy blend uses a mixture of solder powder sizes, which may have an effect on both the materials' printing and reflow process windows. Figure 4 shows typical powder size distribution data for the anti-tombstone powder blend vs. conventional Type 3 and 4 powder sizes.

Pastes using this alloy blend show improved aperture release and volume consistency when printing through stencil apertures for 0201 passive devices and 0.5 mm pitch chip scale packages (CSP) because of the slightly superior particle packing in pastes containing the wider size distribution in the blended alloy compared to that of the Type 3 and 4 materials.

The reflow process window for the anti-tombstone powder blend is the same as Type 3 powder and does not show the slight compromise that accompanies the use of Type 4 powder. The anti-tombstone powder blend's surface area is higher than in Type 3 powder (and makes greater demands on the flux) but not as large as in Type 4 powder. SMT

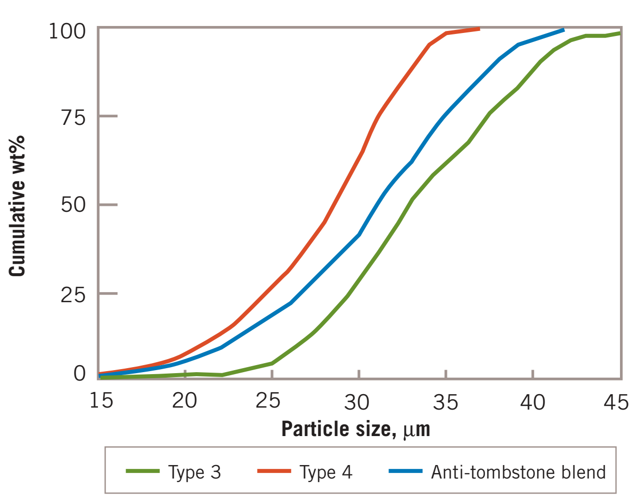


Figure 4. Typical cumulative powder size distributions. The anti-tombstoning blends also have demonstrated improved stencil-aperture release.

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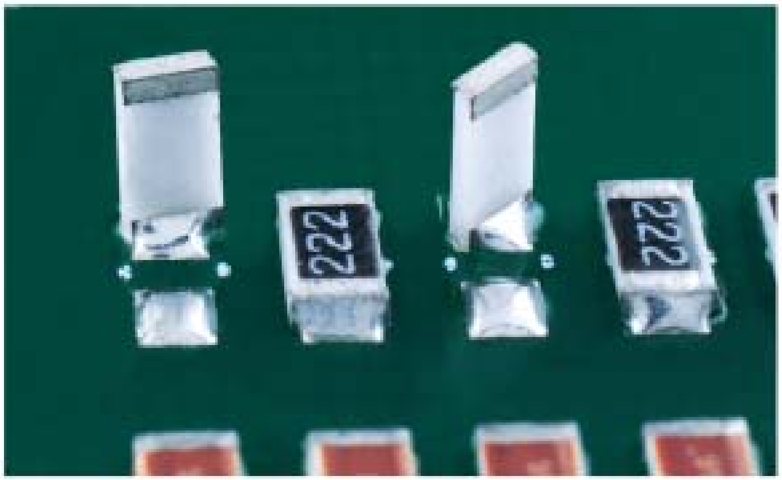
Anti-Tombstoning Solder Paste



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Smaller, lighter components such as 0402 and 0201 chips are creating a tombstoning epidemic in the electronics industry. The unique alloy in Multicore® 63S4 is designed to eliminate costly tombstone defects and reduce component misalignment that occurs when reflowing boards with very small components.

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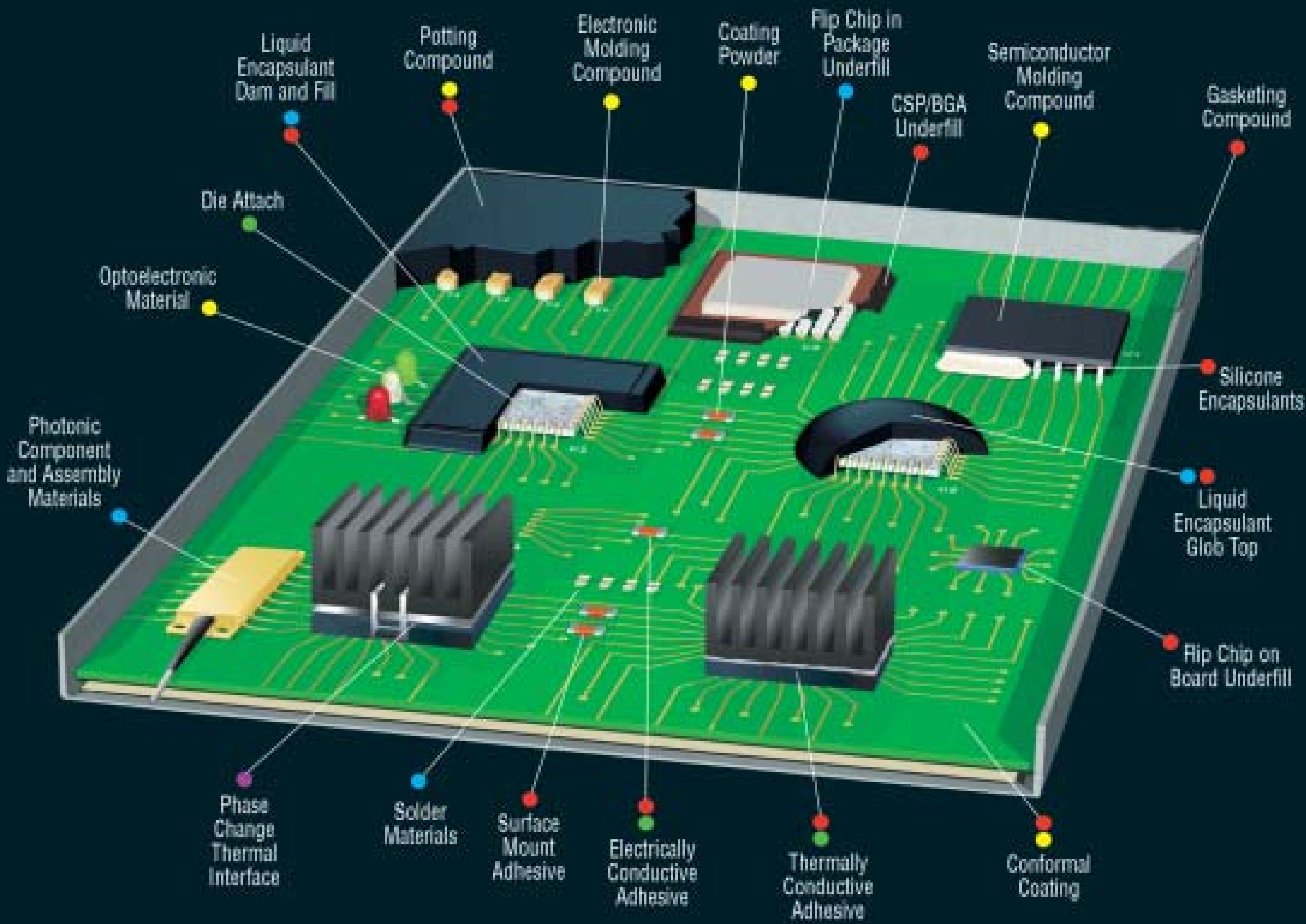

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