Area Array Encapsulation with Stencil Printing and Microwave Curing

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Abstract

An alternative to the transfer molding of area array packages is the stencil printing of the encapsulant followed by a Variable Frequency Microwave (VFM) cure process. A block of epoxy encapsulant resin was stencil printed over a square array of ICs bonded to a printed circuit board. The board circuitry included tuned microwave structures that focused curing of the edges of the encapsulant while the bulk was cured in the VFM oven at a low temperature in just a few minutes. A void free, fully cured encapsulant was produced with the same dimensions as the stencil and with satisfactory mechanical properties.

Stencil Printing of Encapsulants

Encapsulation is commonly used to package chip-on-board, wire bonded IC's, thin die, stacked chips, and backside die cover. Transfer molding is the most well established encapsulation process and is used widely because it is fast, the material is generally cheap, and the process is capable of producing very flat surfaces and crisply defined edges. A dam and fill dispensing alternative is a serial process which is severely limited by speed.

Stencil printing can also be used to apply liquid encapsulation materials on delicate electronic components to form discrete protective coatings en masse. Printing is achieved either by using conventional squeegee blades or by enclosed print head technology. Compared to transfer molding, stencil printing is less costly, less complex, has lower material waste, and a shorter lead time for the stencil. The environmental issue of transfer mold waste disposal has lately become a serious problem. More recent interest in the stencil printing encapsulation process has been observed with delicate IC assemblies which may not survive the heat and pressure of transfer molding.

Voiding and slump are typically the two biggest performance concerns for a stencil print encapsulation process. Custom encapsulation materials capable of sustaining better deposit control is producing improved results but formulation modification is not always desired or is compatible with the printing process.

Low Temperature Curing and Void Removal

Fast and selective VFM curing of epoxies and other polymers is an established process in volume production for a variety of applications. Recently there have been applications of VFM for lowering the cure temperature of epoxies [1], polyimides [2,3], PBOs [4], and other materials. Microwaves uniformly cure the whole bulk of a material. This provides a low stress, uniform, large-network cross-linked polymer. Another feature of VFM curing is a substantial reduction of residuals in cured polymer films. These advantages led us to try a rapid cure of stencil printed epoxy encapsulant that might avoid the slump of the printed area as well as remove the voids created in the printing process.

Unfortunately, even though the encapsulant edges could be cured in 90 seconds or less with less than 1.0 mm shrinkage, the cure across the array was not uniform. Since the microwave energy is absorbed by both the epoxy and the IC, the areas above and very near the ICs were more cured than the areas between the ICs.

It was also found that a slower ramp to cure temperature and a lower soak temperature were favorable to the removal of voids. This slower cure process (6-12 minutes) was much too slow to overcome the nearly immediate reduction in viscosity of the epoxy as it warmed to cure temperature. The material would slump and flow to the edges of the board.

The "onset" and "peak" temperatures of one encapsulant (Loctite CNB 951-43), are 126°C and 152°C respectively. The standard cure profile for this material is 125°C for 60 minutes followed by 150°C for 90 minutes. The first step at 125°C (below the gel point) is to allow a more open network cross-linking and thus produce lower shrinkage in the final film [5]. The second step at 150°C is to complete the cure and provide good adhesion.

Statistically designed experiments (DOE) were used to find the time (5-20 min), temperature (105°C-120°C), vaccum (400-760 torr) and ramp rate (0.1-1.5 °/s) that would give satisfactory cure, adhesion and void removal. It was found that lower vacuums (<300 torr) would produce too rapid an evolution of the voids and a pitting of the surface of the encapsulant. Microwave energy heats and expands the voids as they escape so they must be allowed to evolve gently. The cure temperature also needs to be below the gel point of the epoxy to prevent void entrapment.

There is no need for a second, higher, cure step with VFM since the epoxy is already fully cured. Adhesion tests have shown low temperature VFM to be at least as good as with higher temperature curing [6].

Printed Edge Curing

VFM energy is generally reflected from metals and the rapidly changing (25υs) residence time of any one frequency does not allow for charge build-up or arcing. However, microwave energy can be focused under exactly the right conditions. A metal wire in air with the length of approximately ¼ of the wavelength of the microwave source will focus that energy efficiently.

If circuit board traces are properly designed to account for the dielectric media around them, these "wires" can be used to bring high local heat to very specific areas or patterns on the boards. If traces could be added to the array carrier boards around the edges of the printed encapsulant it might be possible to provide sufficient additional localized heat to prevent the edge of the epoxy pattern from flowing during a measured cure of the bulk material in the middle of the pattern.

Antenna and Board Designs

A series of experiments were conducted to determine the design parameters for efficient focus of energy by microwave "antennas" in the circuit boards.

- Single line pairs (with gap)
- Double line pairs (offset)
- Triple line sets (offset)
- Quadruple line sets (offset)
- Perpendicular pairs (with gap)
- Crossed line pairs (offset)
- Closed lines (rectangles)

Figures 1 & 2 show the board designs that incorporate all of these line geometry experiments.

The simplest design is a series of single lines around the border of the encapsulant (Figure 3). The line lengths were increased slightly from the wire-in-air case of ¼ wavelength due to a slight slowing of the energy through the dielectric material (FR4 or BT) of the board around the traces. The widths and thicknesses were chosen to be similar to the other circuit trace widths and copper thicknesses likely in chip carrier designs.

As with most antenna designs, there is more energy absorbed at the ends of an antenna than in the middle. A series of multiple line designs were evaluated to determine if a more uniform heating would result from staggered parallel traces. There is also a need to turn corners around an encapsulant area so it was necessary to find designs that could either be bent or crossed to produce a library of shapes for any possible array size. Clear antenna design rules are also necessary to prevent the inadvertent addition of antennas in the rest of a circuit board layout. The same design was applied to FR4 and BT materials and a selection of copper thicknesses.

Results: Low Temperature Cure

From the DSC of the epoxy (Figure 4) it can be seen that the temperatures used for the VFM cure are at or below the "onset" temperature. It is important to keep the VFM cure below the gel point to allow the bubbles to move to the surface and escape. By using this low temperature the shrinkage and stress are reduced as well [1,5,6]. Cures from 88-100% resulted within a time range of 10-20 minutes for this material. Ramp rate was insignificant in the range of 0.5-1.5 °/s but further trials are underway at lower rates especially since the ramp only adds a few minutes to total process times.

Results: Void Removal

Most voids can be removed from printed encapsulants with a vacuum of 5-10 torr for about an hour (Figure 5). With concurrent heating by VFM, vacuums of 100-300 torr caused excessive void transport and eruption. A minimum vacuum of 350 torr produced smooth removal of all voids remaining from the stencil printing process during VFM curing (Figure 6). A pressure of 400 torr was used in further experimentation.

Results: Antenna Design

Substrates made from FR4 and BT were designed in a statistical array to determine the optimum antenna length, width, and thickness for focusing microwave heating. The amount of heating at the antennas was measured by the relative burning of temperature sensitive paper in contact with the surface of the substrates. These measurements were later confirmed by the amount of cure of epoxy placed directly on the circuit traces.

For the single lines, the lengths were centered around a little more than ¼ of the central frequencies of the two VFM machines used in the studies (C-band and X-band). The widths are common PWB capabilities and the gaps are the distances between the ends of the lines. Thicknesses were chosen as "half-ounce" and "quarter-ounce" copper (8 & 16 um). Trace thickness was a blocked variable.

- Microwave frequency: 5.85-7.0 GHz
- Length: 15.64, 17.0, 19.0, 21.0, 22.36 mm
- Width: 0.07, 0.10, 0.15, 0.20, 0.23 mm
- Gap: 1.32, 2.0, 3.0, 4.0, 4.68 mm

These DOE results are shown in Figure 7. The optimum line length is clearly lower than 17 mm and additional experiments are refining that number. The optimum was close to 1/3 of the center of the wavelength range. The width of the lines only had a small effect in the range of 0.1 to 0.2 mm. The thickness of the copper was insignificant and the gap between lines of must be less than 1.5 mm to assure continuous heating across the gap.

- Microwave frequency: 7.8-8.7 GHz
- Length: 13.32, 15.0, 16.0, 17.0, 16.68 mm
- Width: 0.07, 0.10, 0.15, 0.20, 0.23 mm
- Gap: 1.32, 2.0, 3.0, 4.0, 4.68 mm

These DOE results are shown in Figure 8. The results are essentially the same for this frequency band. The optimum length is less than 14 mm which is close to 1/3 of the center of the wavelength range. Thickness and width are insignificant and gap must be less than 1.5 mm.

The uniformity of heating for the double, triple and even quadruple line sets was unexpectedly poor. There were heated areas but they did not extend to the ends of the patterns as shown by the shadowed areas in Figure 9. There may be more refined designs with multiple lines but the width of these sets preclude their use in most of these applications.

Perpendicular pairs of lines and crossed lines gave inconclusive results and will require further study with epoxy trials. As expected, the closed rectangles and squares did not heat appreciably. Single lines separated by gaps appear to be adequate for most applications without resorting to more complicated structures. The broad energy absorption of epoxy polymers may be forgiving enough to allow simple turns in design rules.

Most of the above experiments used BT substrates and a small selection of epoxy encapsulants. The more temperature sensitive FR4 boards will require designs that are de-optimized to prevent any burning of the boards from the focused energies at the antennas. Some of the epoxies studied also had more difficulty with the elimination of voids or the escape of the voids from the surface of the "block". Material dependencies are candidates for further study and offer better understanding of the curing mechanisms.

Results: Print and Cure

The true test is the printing and curing of encapsulant on an array of bonded dice. A simple test board was built to hold an array of ICs and a matrix of single line antenna designs (Figure 10). Since the X-band range was used, line lengths of 10 mm and 13 mm were used and widths were increased to 0.2 mm and 0.5 mm. When a border of lines exceeded the circumference of the encapsulant area, the last lines were shortened and allowed to extended beyond the ends.

Figure 10 also shows that the total width of the line borders changes from 51 mm to 48 mm. These were chosen to provide positions of the traces that were 0.5 mm outside the 50 mm stencil opening to 1.0 mm inside the stencil openings respectively (Figure 11). The width of the encapsulant before curing is actually 51 mm due to a typical 0.5 mm slump of material between the time it is printed and placed into the oven as depicted in Figure 12. The amount of slump from curing is measured as anything above 51 mm.

The results of boards stencil printed and VFM cured show that the 48, 49, and 50 mm antenna borders slumped and flowed well past the 51 mm starting widths. However, the 51 mm antennas showed sharp edges at the 51 mm widths with no slump or flow. Clearly it is necessary to have the antennas at the edge of the printed epoxy area to heat the material intensely at the border and prevent slump in the bulk. A close up photo (Figure 12) shows a sharp epoxy border at the edge of the copper antenna line.

Conclusions

It has been demonstrated that a large area array encapsulation of ICs can be performed by stencil printing followed by VFM void removal and curing. This process used efficient material deposition; produced low stress films; was fully cured without voids in minutes; and retained the geometry of the printed encapsulant without slumping or flowing. This process may become a superior alternative to transfer molding or dam and fill dispensing.

Acknowledgements

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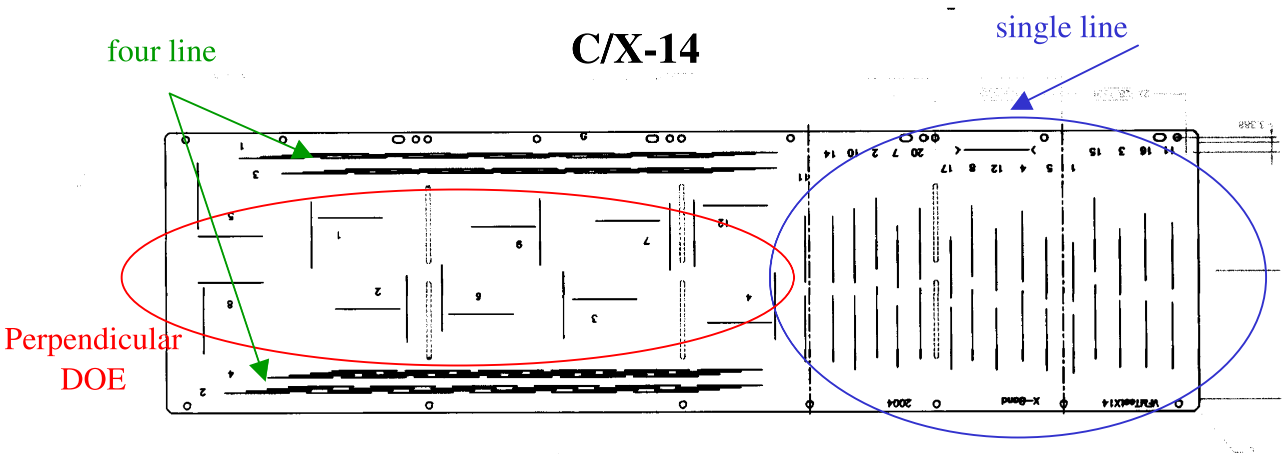


Figure 1

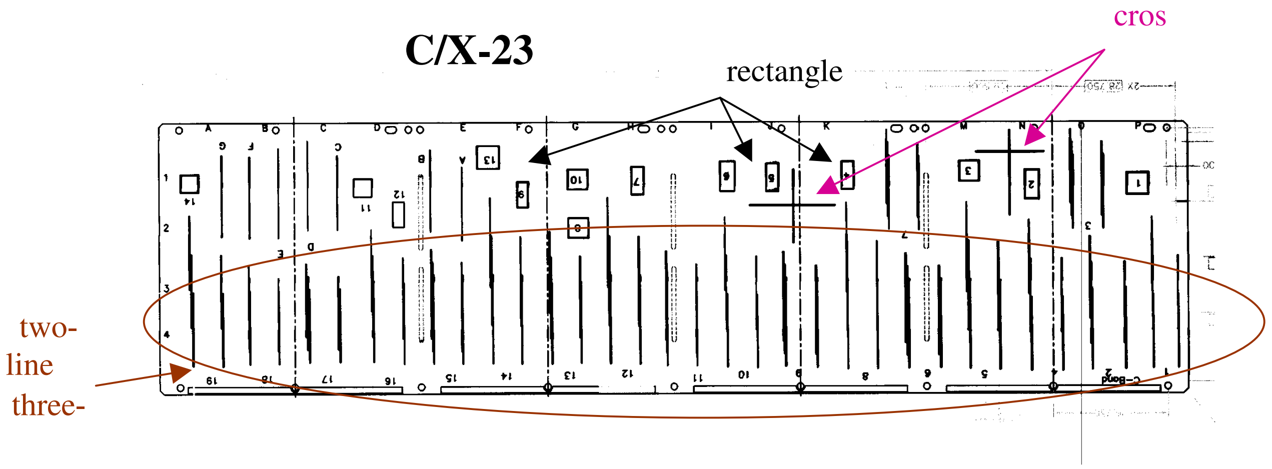
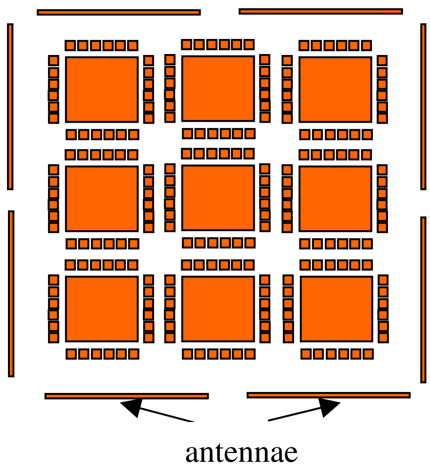


Figure 2



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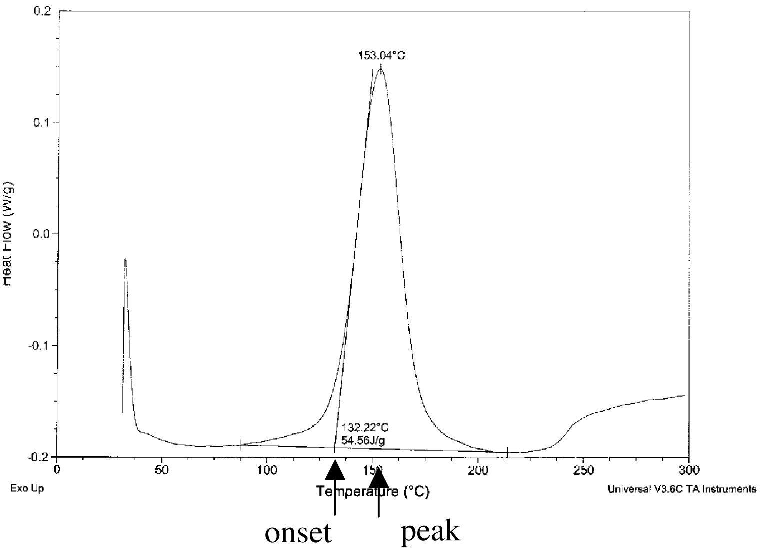
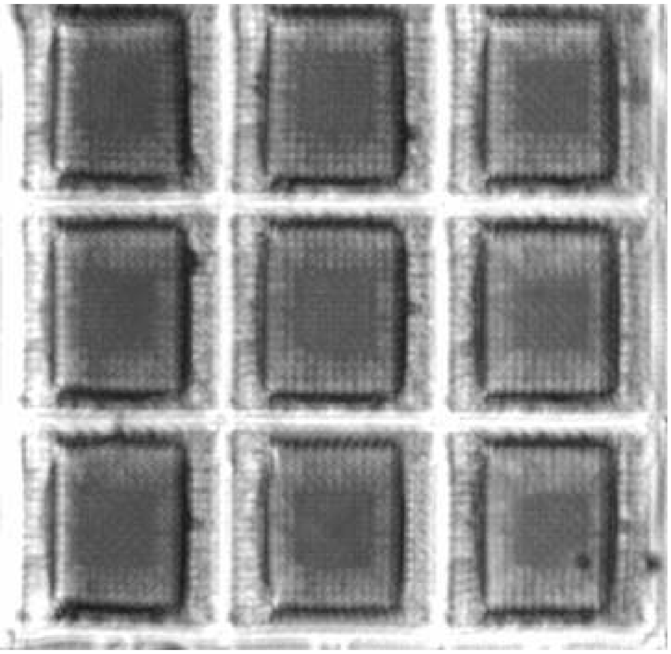


Figure 4



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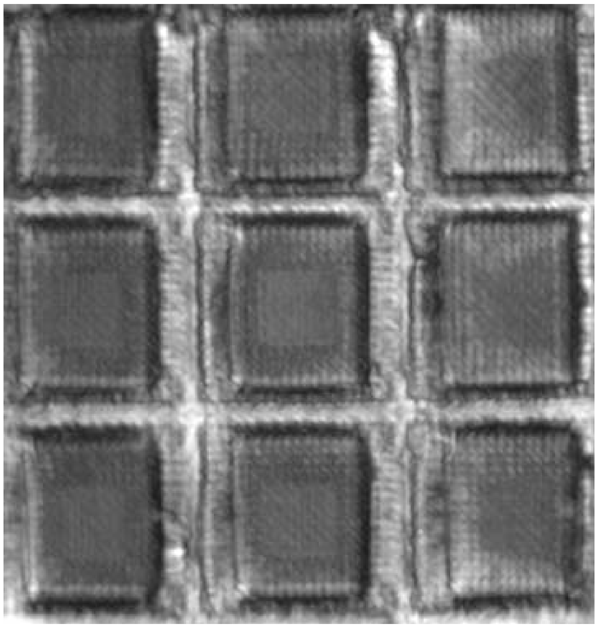
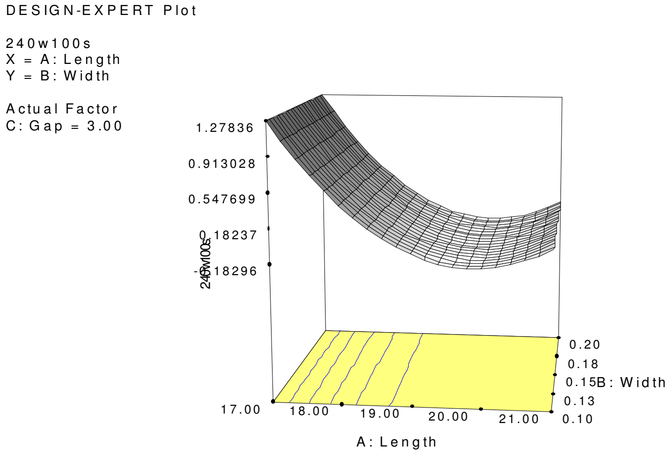


Figure 6



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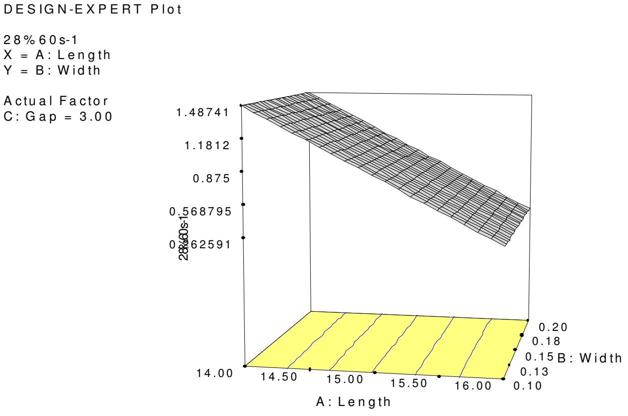

Figure 8

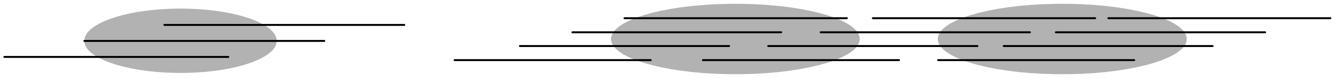

Figure 9

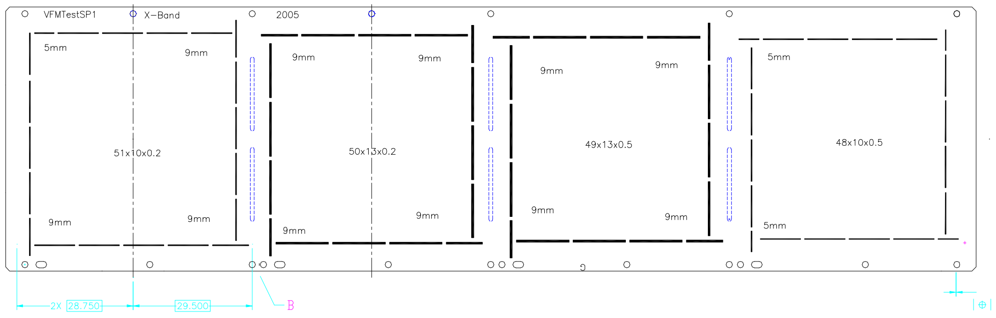

Figure 10

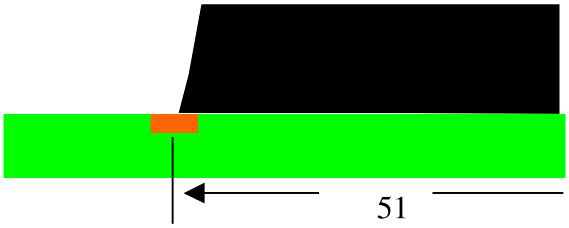

Figure 11

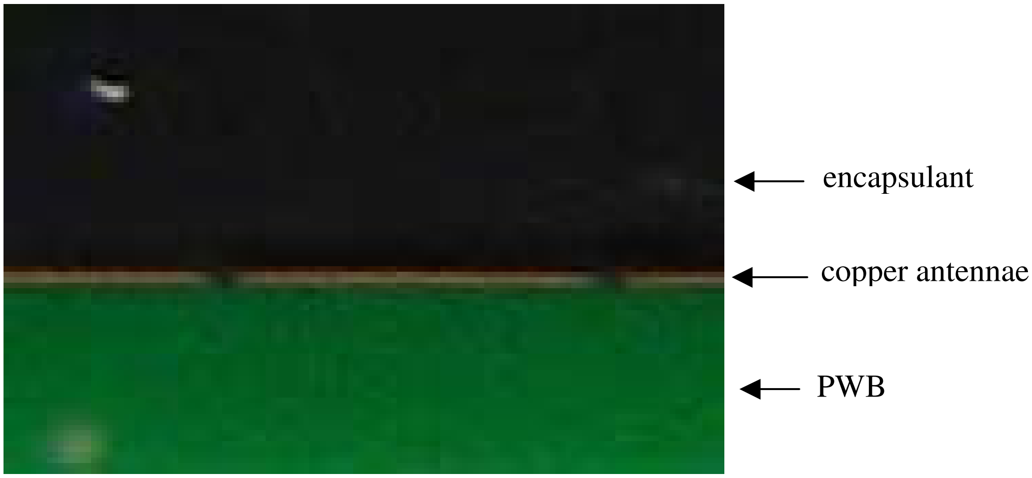

Figure 12