Advanced Printing for Microelectronic Packaging

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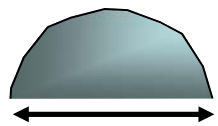
Abstract
Using micro-dispensing with exceptional volume control it is possible to print in 3D space a wide variety of materials and including solders, epoxies, conductive adhesives and ceramic filled polymers. These can be used to build 3D structures and utilizing a 3D Printing approach which is also known as Computer Aided Design and Computer Aided Manufacturing (CAD/CAM). The advanced technology enables 3D printing of electronics but it also enables smaller solder and adhesive dots; 75 microns and less. It is possible to place these on any package in 3D space. Demonstrations for this technology have shown that it is possible to print less than 50 micron wide lines and dots. Additionally a wide range of materials that will be required in future packaging can be dispensed. These smaller features provide sub nanoliter volume. This is possible given the less than 100 picoliter volume control during dispensing and including highly viscous materials. Demonstrations of smaller printed dots and lines for electronic circuits and packaging will be shown. In addition, 3D circuitry that is 3D printed and contains no solder will also be shown, demonstrating the future of printed circuits.

Introduction
Electronic packaging has been a stable research topic since the vacuum tube era. These were physically large and fragile devices and typically the electronic connection was a mechanical socket that ensured good contact over a large surface area. The issues involved were both electrical contact and mechanical security or ruggedness. The evolution of electronics from vacuum tubes to semiconductors presented opportunities to shrink the electronic devices without reducing the performance. This dramatic change forced a change in connections as well and the idea of mechanically connecting electronics needed to be studied. Solder was a very old, literally thousands of years old [1], technology, but for electronics was a natural fit. A natural fit given two reasons, one was the obvious electrical attributes, but the second was the mechanical flex that solder could provide between two joining surfaces [2]. This became especially important with two dissimilar surfaces. Solder also became its own research topic and the growth and maturity of this process has proven to be one of the most important contributions to electronic packaging since the semiconductor; almost all electronic devices today have solder. The mechanical bond was important, but this alone was not enough given the rugged requirements of some of the electronic devices. The extra ruggedness would be provided using mechanical devices and if the electronics were too small, then another technology that was also thousands of years old was used, glue [3]. Adhesives primary contribution was to enhance ruggedness but adding features such as conductivity to adhesives provided additional value. Solders and adhesives are an important part of electronic packaging and the future of electronics is to increase functions per volume which implies tighter pitch and smaller traces, smaller pads, smaller solder dots and finer features in adhesive patterns. This requires improved methods for applying solder and adhesives. This paper will cover in part, advanced dispensing of fine resolution solder and adhesive dots and lines.

Additionally, just as electronic packaging has evolved from mechanical connections to solder, a future of monolithic electronic packaging will evolve. The idea of circuits in structures has been presented previously by Church et el [4]. Additional demonstrations of printed circuit structures will be shown and the concept of using similar technology to dispensing dots and lines of solder and adhesive will be explained. The concept of dispensing a wide range of materials in three dimensions presents a potential change in electronic packaging. This paper will cover the concept of combining dispensing technologies on a single platform to build integrated and monolithic electronic structural circuits.

Micro-dispensing

There are a number of technologies that can be utilized for micro-dispensing. The technology utilized for the results in this paper is from the standard nScrypt SmartPump™. The SmartPump™ has two distinct characteristics that have proven a significant advantage for dispensing very small volumes of solder and adhesive. The first is the specialty shaped pen tip that allows extremely high viscosities (greater than 10 Mcp) and the second is the valve in proximity to the pen tip for exceptional control. Very small volumes such as single digit nanoliter or even less than nanoliter volumes are dimensions of interest with respect to dot size. 300 micron pads are of interest for solder, but the future of solder pads will be much small than 300 microns; 100 microns and less. A 100 micron solder dot will be a need in the near future and it is even conceivable to move toward 50 micron solder dots. A 300 micron solder dot will have a volume of approximately 8 nanoliters (assuming a half sphere shape). An 80 micron solder dot will have a volume of approximately 130 picoliters, a fraction of a nanoliter. Figure 1 below is a table showing ½ sphere shaped contours diameter versus volume. Controlling small volumes in a repeatable manner will be important when considering small volumes.



Half Sphere Dot

Diameter (µm)	Nanoliter
10	0.00026
20	0.00209
40	0.01676
80	0.13404
160	1.07233
320	8.57864
640	68.62908
1280	549.03265

Figure 1. Half sphere diameters converted to volumes.

In addition to dots, there is the need to print fine lines of adhesives or conductive adhesives and other materials. Adhesives can vary significantly in material attributes. These attributes are such properties as viscosity, thixotropy and particle loading. The ability to print adhesive materials consistently and also handle the wide range of diverse properties from the vast array of available materials can be important. The contribution this team has made is to do that with exceptional control for small volumes, provide finer features of 150 microns or less and to control the starts and stops of the dispensed lines and features.

A number of important printing factors need to be considered when printing fine lines. One is the diameter of the pen tip. Typically the inner diameter does not set the width of the dispense feature; this is usually set by the out diameter of the pen tip. In addition, there is a slumping issue. Most shear thinning materials will slump after being printed. Therefore to print a fine feature such as 100 microns, it is many times necessary to go to a smaller pen tip such as a 50/75. This implies 50 micron inner diameter and 75 micron outer diameter. Additionally, it will be important to get in proximity of the substrate. Proximity is affected by the pen tip diameter. If the diameter is very large (hundreds to thousands of microns) then the gap set between the pen tip and the substrate can be very large. The volume being dispensed will be very large. If the desire for small features is important, then the small gap will be important. Gaps on the order of microns and tens of microns can have an effect on printing as well. The flow rate for dispensing can be affected by the gap.

The flow rate of the pump (which determines the dispensed feature size) depends on the value of the pressure, the valve opening and the size of the tip orifice. Engineers and researchers at nScrypt also discovered that the dispensing height (the gap between the dispensing nozzle tip and the substrate) plays a crucial role in the dispensing volume and especially when the feature size gets smaller or thin lines are printed. For these types of features the nozzle tip needs to be closer to the substrate. This will increase the flow resistance and thus reduce the flow rate. It is expected that the pressure drop will be dominated by the dispensing gap when the gap is 50% smaller than the tip size. By applying the above mentioned CFD model at various dispensing heights (Figure 2), the flow rates were calculated [5].

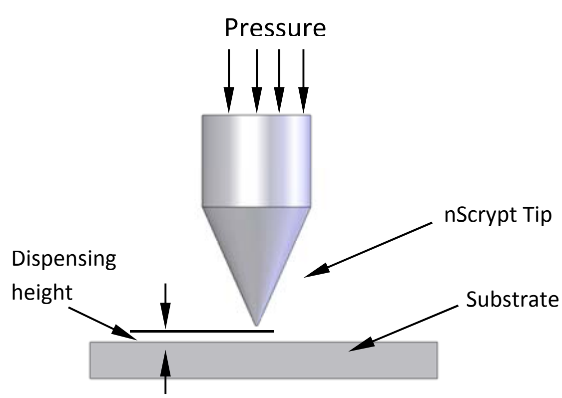


Figure 2. Schematic drawing of the CFD model

The pressure drop with different dispensing heights is plotted in the Figure 3. At a very small gap (Figure 3a), the pressure drop is dominated by the substrate. At a large gap (Figure 3c), the pressure drop is mainly determined by the tip orifice. There is a transient region (Figure 3b) where the pressure drop is affected by both of them.

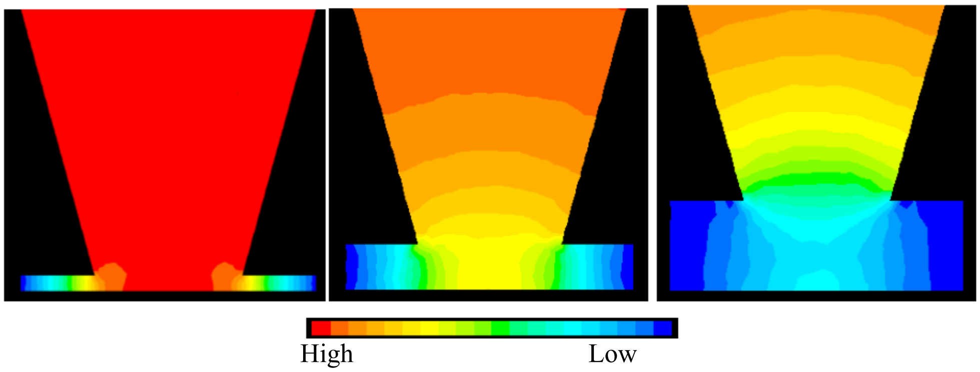


Figure 3. Pressure drop vs. different dispensing height. (a) 5 microns. (b) 15 microns. (c) 30 microns.

The flow rate vs. dispensing height is plotted in the Figure 4. It can be seen that the flow rate increases to a steady state value at the dispensing height that is proportional to the value of the pen tip diameter. The pressure moves the steady state flow rate with the lowest pressure achieving steady state the fastest. It is also obvious that the flow rate is sensitive to a change in dispensing heights if they are below a certain value (50 microns in this case). The lower the dispensing height, the more it affects the flow rate.

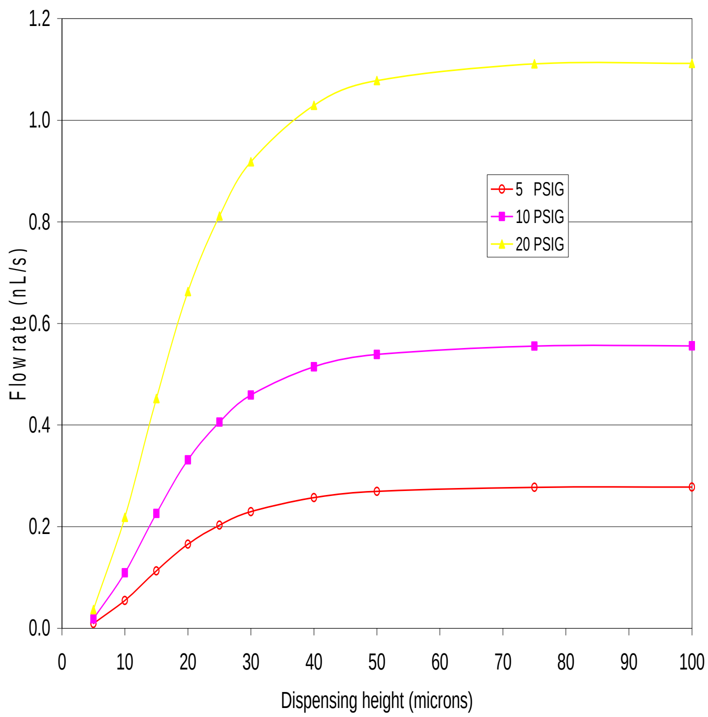


Figure 4. Flow Rate vs Dispense Height

From the analysis above, we can find that it is important to control the dispensing height for small or thin features. nScrypt's tool has height sensors integrated for this purpose. The surface to be dispensed on is either pre-scanned or real-time scanned. The height data will then be transferred to the controller to create a surface contour. A constant dispensing height is maintained during dispensing by following the surface contour, which makes it possible to dispense on highly conformal or on twisted surfaces, but it should be noted that even "flat" surfaces are not truly flat when dealing with micron resolutions.

Micro-dispensing Small Solder Dots

A 15x15 array of solder dots were dispensed using the SmartPump™. A 100/150 pen tip was used. Print frequency was 4 dots per second using a 1 millimeter Z lift between dots. The viscosity of the solder was 100,000 cp. Dots were dispensed in at a set distance apart to form a matrix and the printing gap was 30 microns. A constant pressure of 8 pounds per square inch (psi) was used. The pressure was not varied and was set at a value that matches the flow rate of the desired dispense rate. The pressure was strongly dependent upon the viscosity of the material being dispensed, the inner diameter of the pen tip and the shape of the pen tip. The solder was comprised of multiple materials and including a flux which could separate if the pressure was too high. There are some materials that are dispensed at pressures of almost 100 psi but that much pressure could separate the flux in solder paste. The ability to use low pressures for printing was unique and was attributed to the patented nScrypt shaped pen tip. The solder dots averaged between 75 and 100 microns in diameter depending on the parameters being used. This was a proximity dispensing approach, it was not a jetting action and therefore the gap was a critical component for consistency. The material makes contact with the substrate and the pen tip simultaneously. The surface tension of the material and substrate combined with the pressure of the pump created a consistent dot pattern. The dot patterns can be seen in Figure 5 below.

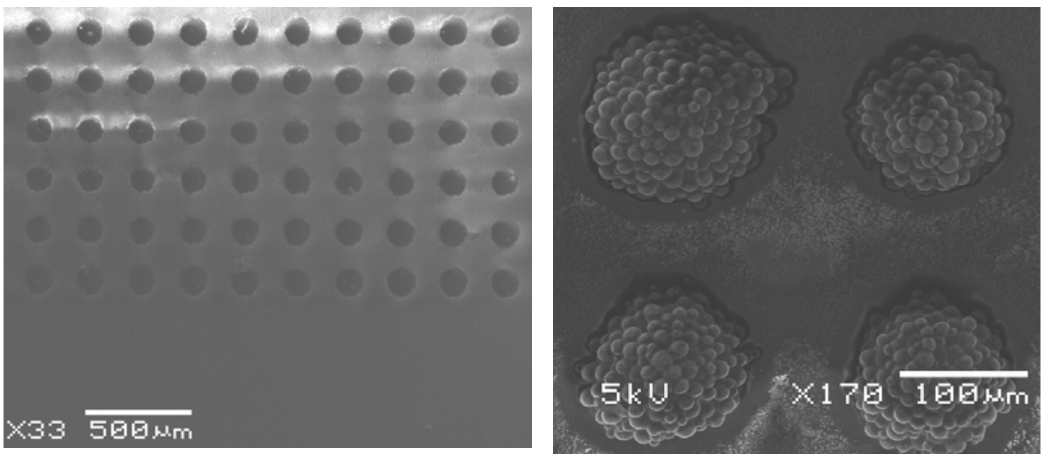


Figure 5. SEM photos of solder dots.

The size of the pen tip was chosen because the solder paste is comprised of metal particles and the average particle size was approximately 15 microns in diameter which could clog smaller pen tips. It also allowed for enough material to be dispensed during the rapid print time. It is interesting to note that SEM or other photos of solder dots typically appear like large mounds of tiny particles, but the SEM photos in Figure 5 show the individual spheres were prominent looking. This was due to the size per mound ratio. The SmartPump™ allows for significantly less particles per mound to be printed and controlled during the dispense process. A number of prints were done and while this process was not optimized, it was demonstrated that prints of this type could be done and controlled. Figure 6 below shows a plot of the array.

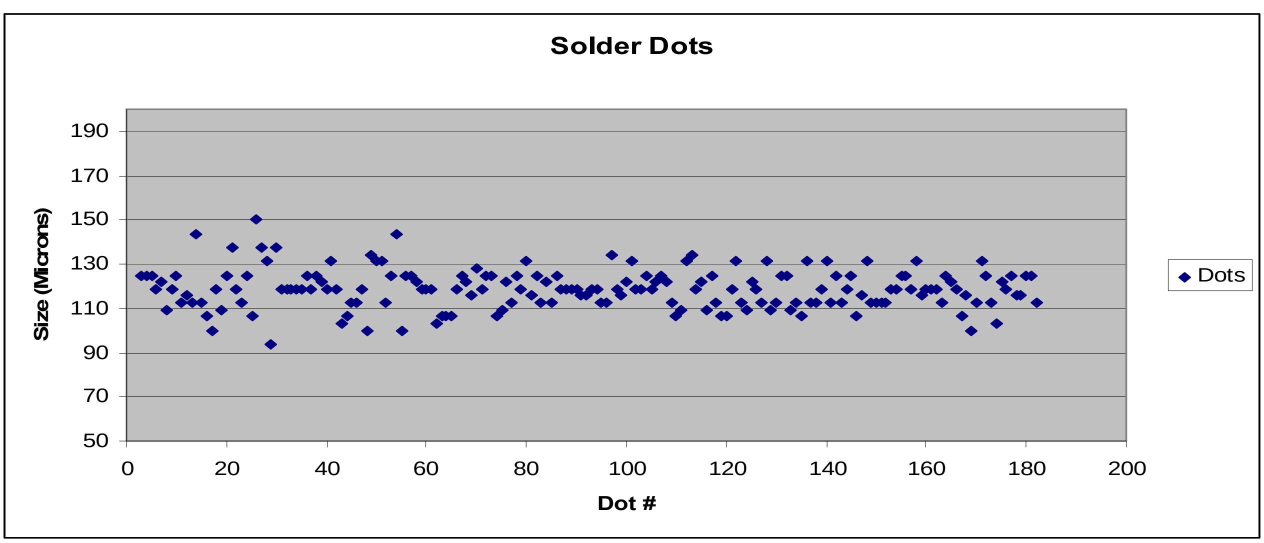


Figure 6. Scatter plot of the dot number versus the dot size.

Micro-dispensing Adhesive Fine Features

A 9x12 array of silver epoxy was dispensed using the SmartPump™. The features of the print consisted of one vertical and one horizontal line that formed the shape of a cross (see figure 7 below.)

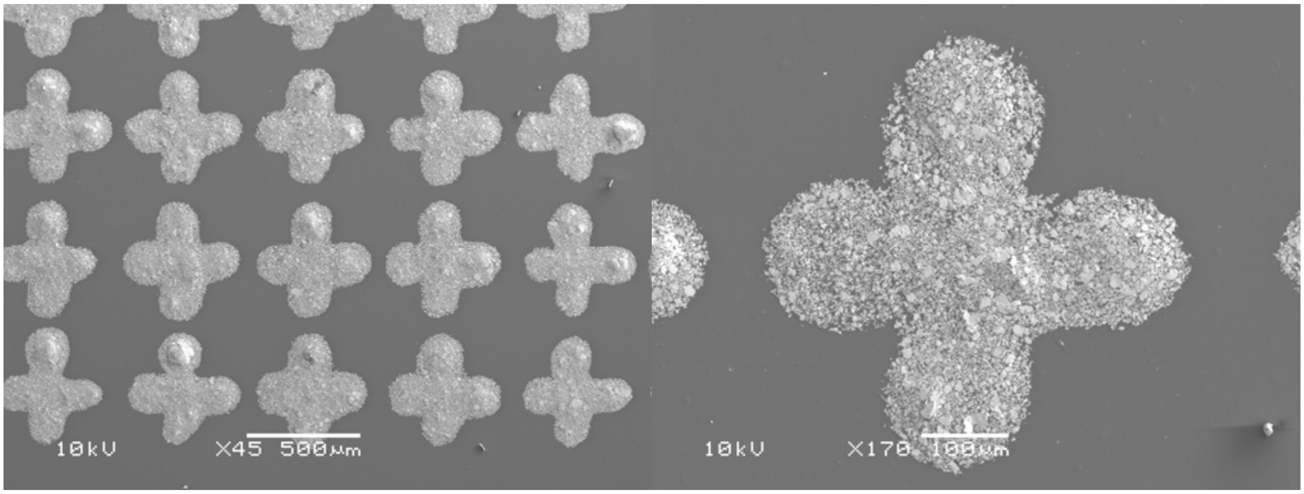


Figure 7. SEM photos of printed silver epoxy patterns.

The print was done using a 10µm gap. The pen tip used was a 100/150. A constant pressure of 12 psi was also used. To control the starts and stops, a pre and post travel in both the Z and X or Y was used. Even with the extra travel, the print was still done at approximately 3 hertz. The average cross was approximately 150 microns wide and had a line length of approximately 450 microns. The line length could be adjusted to any size using a digital input. The shape of the patterns was reasonably consistent however they were not identical. It is interesting to note that there appears to be a correlation between the line length and width. The variation is more than likely due to the gap variations that would occur on non-perfect surfaces. If the gap is less than 10µm, the pressure push back may have an effect on the volume being dispensed. Pre-scanning would enable a tighter control if needed or the other alternative was to raise the gap above the critical pressure feedback height. The crosses were characterized by the average length of the two lines and the average width of the two lines. Although the print was not optimized, Figure 8 below shows the accuracy achieved.

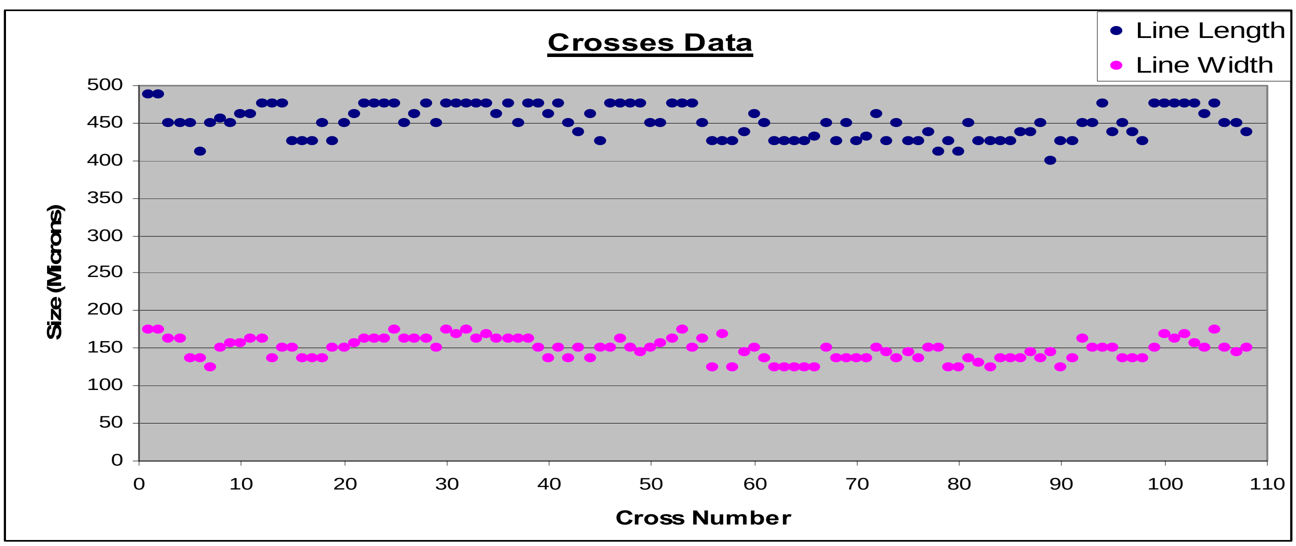


Figure 8. Scatter plot of the pattern number versus Line Width and Line Length

3D Printed Structures Using Micro-dispensing and Fused Deposition

Micro-dispensing for electronic packaging is important and has contributed in such areas as solder and epoxies. The contribution of micro-dispensing in future electronic packaging will not diminish. There are other applications that this is viable for and including printed RF shielding [6]. Micro-dispensing will not stop there, but will continue to take more and more of the integrated build and it will continue to evolve and become more prominent in packaging. The combination of micro-dispensing and fused deposition will enable rapid prototyping and production of models and circuits that were not previously possible. A number of researchers are considering 3D printing as viable solutions that reach beyond rapid prototyping [7,8]. Some researchers have started implementing electronics within the structures [9] and including changing the structures to control EM fields [10,11] Full monolithic objects with embedded circuits would become not only possible, but an attractive option that will grow in use and capabilities. Figure 9 is a rendering of a 3D model of a gyroscope with electronics as part of the structure; monolithically fabricated.

Figure 9. 3D Rendering of a Completely Printed Light Up Gyroscope

Utilizing the CAD models, it is possible to 3D print the structure and then combining printed electronics to print the metallic pads, the interconnects and the resistors. Figure 8 below is a demonstration of this process; a 3D printed and printed electronic combination of the CAD model from Figure 9.

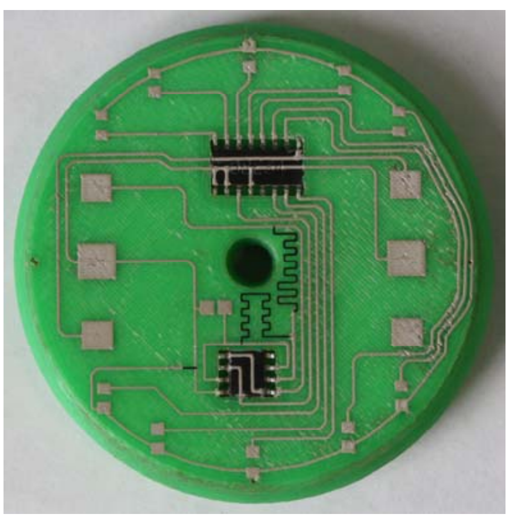


Figure 10. 3D Printed Gyroscope Disc without components

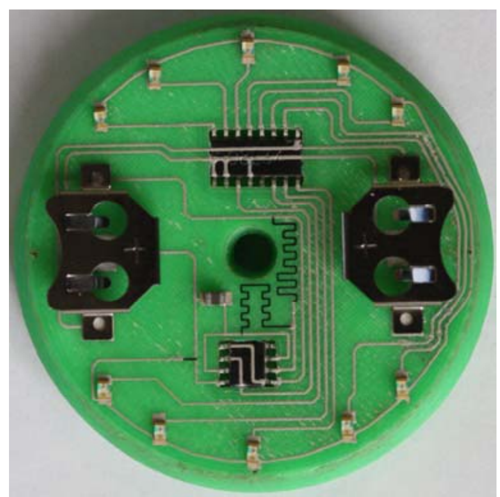


Figure 11. 3D Printed Gyroscope Disc with components

Figures 9 - 11 is a demonstration of the proposed process utilizing the combined techniques. Since these are digital files the shape can be easily changed. The challenge is to make the electronics functional. The printed circuit features 2 ICs, a 555 timer and a 4017 counter, which are embedded upside down in the surface of the printed disc with their legs level to the surface of the disc. It is important that there is a smooth transition from the legs to the surface of the FD part. A gap between the surface and the leg can cause a break in the printed trace. The traces for the circuit were printed using a conductive paste with a curing temperature below the glass transition point of the thermoplastic that the printed part is created from. This prevents the FD part from warping during the curing process. The traces were printed not only on the surface of the printed part, but also on top of the ICs themselves. The resistors required for the 555 timer and LEDs were also printed using a paste with a low curing temperature, and a resistivity of 50Ω/☐ The resistors do not need to be printed in a straight line, but may be printed around obstacles such as the hole in the center of the disc.

The traces and resistors were both printed with a tip ID of 100 µm and a dispense height of 60 µm. As such, it is important to ensure that the surface of the FD part is smooth; otherwise breaks in the traces will form. Furthermore, even slight variances in the height while printing resistors can cause the resulting resistivity to be unpredictable. As a FD part rarely has a surface smooth enough for optimal micro-dispensing, it must be smoothed after it has been printed. The disc in figure 10 and 11 was smoothed by first sanding it with a fine grit sandpaper and then lightly rubbing it with a solvent. This results in a surface that is ideal for micro-dispensing. As FD processes are improved, the sanding and manual smoothing will not be necessary.

One hurdle that does need to be solved for wide spread adoption of this process is the lack of tools designed for both micro-dispensing and fused deposition. As there are no programs designed with this application in mind, multiple applications needed to be used in order to generate the 3D and 2D models needed to print the disc. The circuit diagram was initially created in Eagle, and then exported as a DXF. The disc was then modeled in SolidWorks. The circuit DXF was then imported over top the disc to cut the holes needed to embed the ICs. The disc with the IC holes was then saved as a STL file. The STL was then sliced and converted to paths needed to print the object, while the circuit DXF was converted straight to paths. This long tool chain made modifying the circuit and/or the disc a complicated multi step task. Ideally a single program created with both circuits and 3D modeling should be used.

While this part has its circuit printed on the top, it is not limited to there. After the circuit has been printed it is possible to continue the FD process on top of the circuit embedding it within. Utilizing this method, it is even possible to create full three-dimensional circuits embedded inside the plastic part. This is where the advantages of manufacturing using micro-dispensing and fused deposition will really come to light.

Conclusion

Electronic packaging is becoming more complex given the amount of circuitry required in smaller volumes. This will require tighter tolerances in dispensing and in robotic control for placement. The micro-dispensing of dots and lines utilizing the SmartPump™ has the ability to accurately place and control the volume of solders and epoxies. This could be enabling for existing and future electronic products. Additionally, micro-dispensing was used to demonstrate 3D electrically functional structures. These devices perform like standard electronic boards, but do not require solder. The monolithic builds will be more rugged and as the technology matures this will also add more functions per volume since an additional dimension will be used more effectively.

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