Additive Manufacturing of Printed Electronics

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Abstract

Additive manufacturing is the application of layer manufacturing techniques to fabricate microelectronic products. These techniques differentiate themselves from incumbent technologies in that they only add material to build the device and are an alternative to subtractive technologies such as lithography that globally coat layers and then etch-away unrequired materials. In this paper we discuss an additive technology that performs material evaporation through shadow masks. This process has shown significant potential for the fabrication of chip packaging, microelectronic devices and circuitry; specifically, high density interposers, fine conductor lines and embedded components such as capacitors, resistors, and transistors. The process is compatible with a number of both rigid and flexible substrates and deposition materials. Examples of devices and lines that have been manufactured by this technique are shown and discussed. Preliminary test data shows line / space resolution that has reached 15 / 30 microns and better.

Author Keywords

Fine Lines; Additive Manufacturing; Evaporation-Printing; Thin Film; Embedded Components

1. Background and Objective

The chip packaging and system industry has long sought methods of for producing high quality, small features for interposers and other electronic systems. The industry has also sought methods of incorporating passive and active components into such small features as well. The process under consideration in this writing is the Amax Evaporation Printing™ technology. This technology is under examination as an alternative to the emerging inkjet or bubble-jet technologies due to the benefits as noted below:

	Inkjet [7]	**Evaporation Printing**
Resolution	>10 microns. Current best is 25 microns in lab	14 microns proven. Roadmap to 4 microns
Materials	Must be jettable	Anything evaporable
Throughput	Low	High
Post Processing Required	Heating or Chemical reduction	No
Ability to include inline passives and actives	No	Yes

The goal of this project was to evaluate the ability of Evaporation Printing to make fine conductor lines as well as embedded passive and active electronic components to be used in high density interposers and other chip packaging. The end result of this project is to produce a working, tested interposer for commercial and/or military use using this manufacturing technology.

2. Method

The process under investigation uses the Evaporation Printing method developed by AdvantechUS and is branded under the name Amax Evaporation Printing™. It is an in-line vacuum deposition process that uses critically aligned shadow-masks (stencils) to control the location of the deposits on the substrates. While evaporation coating technology has been in-use for decades, the improvements in the AdvantechUS process come on both the mask manufacture/management and the accuracy in aligning the masks for the various layers.

Unlike many 'printing' technologies, this process does not require any ink formulations or chemical etching that may affect the material properties. The process uses commodity, bulk materials such as copper, aluminum, gold, alumina, nickel, tin, etc. the properties of the bulk materials therefore translate directly into the properties of the devices generated with this process. Since there direct materials are used and the layers are deposited directly upon one another without the need of removing material from the previous layer, the process is considered a green additive manufacturing technology.

The process has shown to be able produce feature sizes to less than 10 µm. This is a major improvement for shadow-masking. Also, aligning the masks during a several step process has previously caused problems. This new process improves greatly the layer-to-layer (mask-to-mask) alignment accuracy to better than 1 µm at 3 sigma. This mask management and alignment coupled with the line-of-sight deposition of the evaporation method allows for very straight side walls and is therefore able to obtain very high quality fine features to build high-quality, micron-scale passive and active electronic components and conductor lines.

The general process has previously been proven in a single chamber system by developing prototype active-matrix backplanes for the OLED and e-Paper markets [1], [2], [4]. Now, the process is being implemented in a 5 chamber in-line system called a miniLine™. This machine is the first-of-its-kind and is capable of depositing up to 6 masks per chamber and 6 material sources per chamber without ever breaking vacuum. Theoretically, there is potential for up to 180+ unique layers per circuit build without breaking vacuum. This would allow for

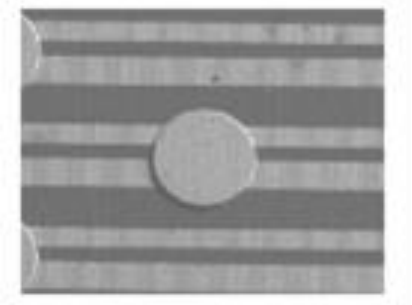
extreme flexibility in the manufacturing of products for the chip packaging and system industries.

Picture 1: Amax minLine™ used for Amax Evaporation Printing™

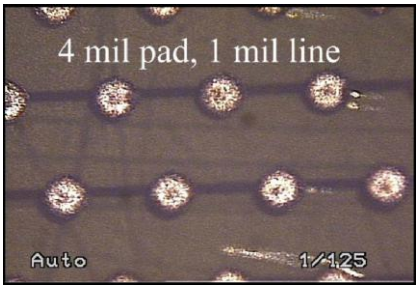
3. Manufactured Test Structures and Devices

A. Fine lines and connected Vias

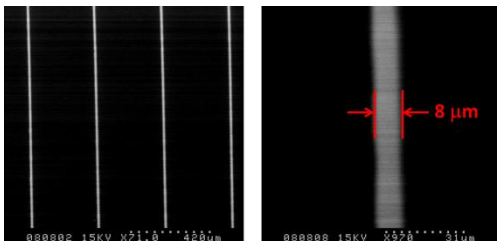
Line features and components have been routinely manufactured with this technology previously from 100 microns down to 14 microns. Typical line widths of the OLED backplanes are 20 microns and have been made for many years with this technology [3]. For the interposer market, testing is currently underway to reach sizes of 5 microns and below with current focus on 8 microns. Pictures 3, 4, and 5 below show examples of prototype structures manufactured.



Picture 2: SEM micrograph of 10 mil pad with 70 micron and 100 micron trace lines with 50 micron spaces.



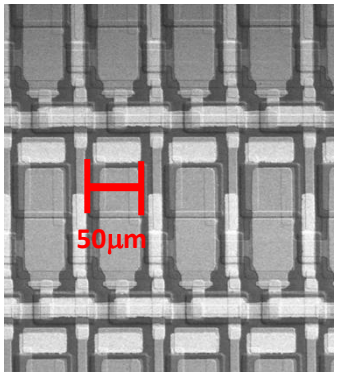
Picture 3: Shown are 4 mil pads with 2 mil vias being connected by 1 mil lines.



Picture 4: SEM micrographs of 8 micron traces this process.

B. Integrated Circuitry

The process has also been shown to make effective integrated circuitry for backplanes. In this case active matrix arrays used for OLED backplanes have been demonstrated as well as single transistor with single capacitor arrays for e-Paper. These arrays contain approximately 240,000 pixels in a 3 inch by 5 inch array [3], [4].



Picture 5: SEM Micrograph of an Active Matrix TFT array

4. Testing Results

Results are broken in to both manufacturing/physical and electrical/device characteristics. Transmission Line results shown below have been validated by the Penn State Electro-Optics Center in Freeport, PA.

A. Characteristic Impedance:

The copper conductor lines were also examined for signal transmission characteristics. The Characteristic Impedance (Zo) of the lines was shown to follow the Wheeler formula for microstrip transmission lines[5]. Representative data is shown below.

Width	Zo (avg, Ohms)
4 mil	32.7
3 mil	40.3
2 mil	51.1
1.5 mil	61.5

1.0 mil	67.9

Table 1: Characteristic Impedance of Microline™ sample

These lines were manufactured of 5000Å copper that was 6 inches in length and compiled using 10 samples per width.

B. Capacitor Uniformity

Parallel Plate Capacitors were made with the process. These devices were 100 square micron area with and a dielectric layer of 3000 Å of Al_2O_3 with pad layers of 1000Å Al. The data was taken using an HP4284A LCR Meter from a random sample of 100 capacitors on a standard panel containing over 14,000 capacitors.

Average Measured Capacitance (pF)	Tolerance
2.31pF	2%
2.76pF	3%
2.08pF	1%

Table 2. Representative Capacitance of this method

C. Resistor Tolerance

Resistors of 30 ohms with line widths of 0.5 mil, and segment lengths of roughly 2mm using a Nickel-Chromium alloy as the resistor and copper as the leads were fabricated with the process. Tolerance was found to be 2.1% over the 600 samples tested with a standard deviation of only 0.63 ohms and a 29.5 ohm average. The data was collected using an automated probe station with Keithly 2100 resistance measurement instrumentation. (See also Picture 9 for example of similar resistor pattern).

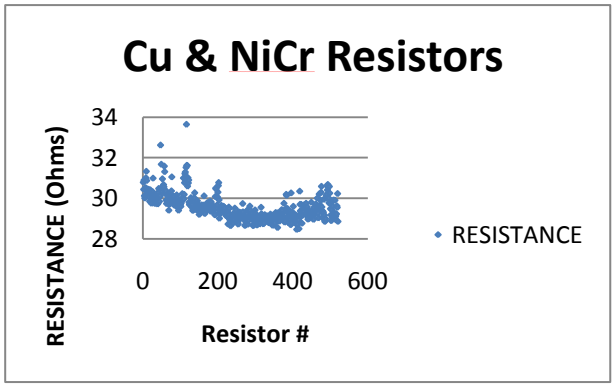


Figure 1: Resistance Measurements

D. Transistor Characteristics:

Figure 1 illustrates a representative transfer characteristic curve for a TFT that is manufactured using the Amax Evaporation Printing™ process. This data was taken with an HP4155B Semiconductor Parameter Analyzer from a random sample of 36 transistors on standard panel of over 14,000 transistors.

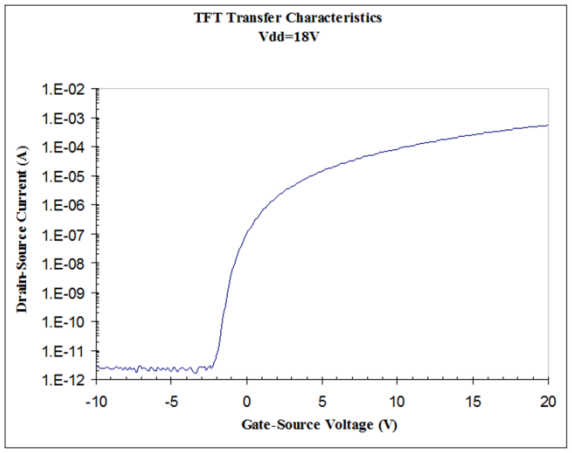


Figure 2: Representative Transfer Curve

Panel Summary	Average	St. Dev.
Vth (V)	1.52	1.03
Mobility (cm2/Vs)	69	29.19
Leakage Current (A)	2.97E-11	1.41E-11
Hysteresis (V)	4.79	1.05

Table 3. Representative TFT Characteristics

Note that the transistors noted had not yet been optimized and therefore have a relatively high standard deviation when this data was collected. However, the mobility of these transistors is very high and with such high mobility, the standard deviation is immaterial for the specific application that was under consideration when this data was collected. TFT optimization is currently underway and expected to be completed in Q1 of 2013.

E. Trace Thickness

The initial trace thickness typically deposited has been 5000Å and lower, though tests have shown the potential of up to 5 microns of thickness dependent upon trace size and design. Plating of thin deposition lines have been developed to get to thicker lines both in this study and by others[6].

F. Defects and Reliability

Defects using this technology have shown to be less than 3 per million opportunities as derived from OLED backplane development. Improvements to further reduce even these opportunistic defects are currently underway.

Also, as further reliability proof, the connected vias of Picture 3 had 0 opens of the 80 connections tested and the resistors examined in section 4.C had 0 opens out of the 600 points tested.

All of which begins to show the reliability of the devices manufactured with the Amax Evaporation Printing™ process.

5. Applications

A. Electrophoretic Displays (e-Paper)

e-Paper displays have been fabricated by using the Amax Evaporation Printing ™ process to make the backplane and then laminating e-paper on top of the backplane. Shown below is a 1 inch by 2 inch dot matrix display with a resolution of approximately 80 dpi.

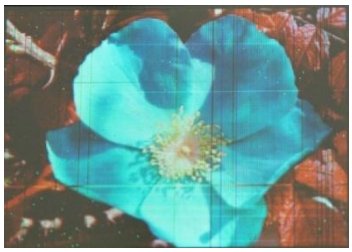
Picture 6: Completed Prototype ESL Display

There are many direct applications of this type display such as signage for grocery and retail store shelving (shelf tags), indicators, watches, cell phones, keypads and a host of other devices.

Picture 7: Prototype flexible ESL display

B. OLED

AdvantechUS has been using the AMAX evaporation Printing™ process for making OLED display backplanes for use in research and development for several years. Pictures 8a and 8b are examples of prototype displays using this technology. These devices were manufactured using a single chamber deposition chamber. The line defects shown were caused by chamber contamination. One critical function of the multi-chamber miniLine™ is to eliminated the particle defects by having multiple chambers that remain under vacuum throughout the manufacturing process. The miniLine, therefore, will eliminate the line defect issue.

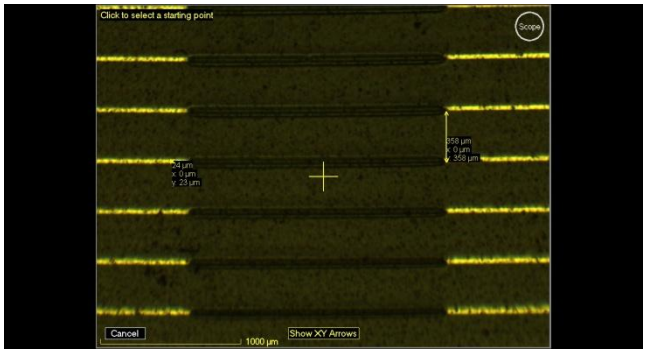


Pictures 8a, b: Prototype R&D OLED Displays using an Active Matrix backplane manufactured with AMAX Evaporation Printing™ Technology

C. Printed Electronics (General)

There are many components of electronics that are compatible with this technology. Resistors, capacitors and thin film transistors have been fabricated numerous times without concern of the application. However, the technology is now to the point where such devices can be made and included in circuitry to reduce the overall size and weight of electronics devices as well as give the added potential of electronics printed on flexible substrates.

Picture 9 shows s test panel of 1500 ohm resistors that are 1 mil wide connected to 1 mil lines. By changing the resistive material, virtually any resistance from single ohms to several megohms per resistor is possible.



Picture 9: 1 mil wide resistors embedded into 1 mil line

D. Chip Packaging

By combining several of the test structures show in this paper, it is envisioned that chip carriers will be a market well suited to this technology as well. By using the sub-mil fine lines technology, current chip carriers can be manufactured. By combining this technology with the printed electronics capability of the

technology to include *inline* resistors and capacitors, it opens a potentially disruptive technology to the printed circuit board market to reduce circuit board size and complexity by putting components closer to the transistor die.

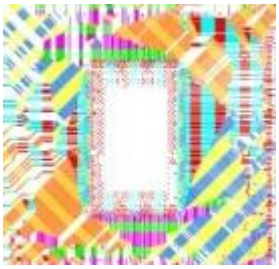


Figure 2: Representative design for an inner layer of an interposer manufactured by AMAX Evaporation Printing™

E. Fractal Antennae Arrays

Since the AMAX Evaporation Printing™ process lends itself well to making complex designs of small featured lines, fractal antennae arrays are well within the scope of this process. With line widths down to feature sizes and a single array being from microns if size to 370mmx470mm in size, many arrays can be effectively manufactures using this process. Also, with the potential use of alternative materials, it also allows for the implementation of smaller, more flexible and more cost-effective arrays than might otherwise currently be in use.

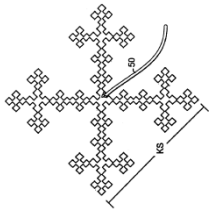


Figure 3: Representative concept of Fractal Antennae

6. Conclusions

The AMAX Evaporation Printing™ process has been shown to be a viable manufacturing method for many high density electronic devices. It is an additive, low cost, green and simple method of making small feature-sized electronics. The technology has been proven with complex backplanes and is now a natural fit to be used with other micro-electronic devices and systems. Though further development and testing is required before commercialization, the initial results show this technology to be very promising in many applications and markets.

References

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