Production of Microelectronic Components by Electrophoretic Deposition

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Abstract

Electrophoretic deposition (EPD) is a particle based, electrodynamic forming process suitable for particles in the micron to nanometer size range. Beginning with a 300 nm diameter silver/palladium powder we have used EPD to produce 5 µm wide conductor lines with a 10 µm spacing on a dielectric tape.

In this process a component is first imaged as a conductive pattern on a plastic film by conventional photolithography. This pattern is then immersed into a stable, dispersed and electrostatically charged suspension of particles. A voltage is applied between the conductive pattern and a counter electrode in the suspension, causing a current flow through the suspension, and attracting particles to the conductive pattern. The current creates an electro-chemical environment at the surface which causes the particles to deposit onto the pattern. This deposition can range from a monolayer to many thousands of particles thick. Using a binder, these deposited particles can then be transferred to another surface to be sintered or fused forming continuous lines or layers. The photolithographically produced conductor pattern can be re-used repeatedly to create more depositions. In this manner a single pattern produced by photolithography can be used to make multiple parts with photolithographic scale resolution.

What is Electrophoretic Deposition?

Electrophoretic Deposition (EPD) can be broken down into three steps: formation of a stable, electrostatically charged suspension of particles in a solvent; electrophoretic migration of particles to the deposition electrode; where, with proper electrochemical conditions, the particles will form an adherent deposit on the electrode surface.

At first glance EPD appears very similar to electrostatic processes, and it is frequently, mistakenly, treated as an electrostatic process.

When an electrostatically charged surface is introduced to a solvent containing even the smallest quantity of ions, ions with a charge opposite that of the surface will immediately migrate toward that surface. These counter charges will screen the electric field from the surface so that there is no electric field in the bulk of the suspension. Positive particles can still deposit onto a negatively charged surface, but without an electric field in the suspension there will be no electrophoresis. Particles will only move to the electrode by convection or Brownian diffusion.

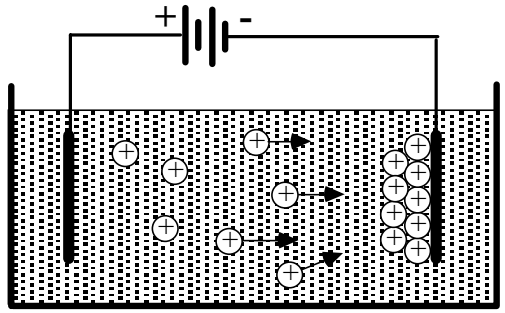

Figure 1. Positively charged particles will migrate to, and deposit on, a negative electrode surface.

During EPD, to maintain an electric field in the bulk of the suspension, ions that migrate to both the deposition electrode and the counter electrode must be neutralized. This can occur either by conversion of the ions into a neutral species or the production of counter ions. In either case, electrochemical reactions at the electrodes are a necessary, and frequently vital, component of EPD.

It is this electrodynamic nature of EPD that leads to its most significant advantage over electrostatic processes. An electrostatic process will be limited by charge density on the deposition surface. The electrostatic charge on the surface of particles that deposit on that surface will screen or neutralize the deposition surface charge. Since surface charge densities are limited, there is a limit to the ratio of the surface area of the particles deposited to the area of the deposition surface.

In EPD a current flows through the system. This means that there is both a continuous flux of particles approaching the surface and a continuous flux of ions through the solvent at the surface. Because of this EPD can form a deposit where the surface area of the particles deposited is tens, hundreds, or thousands of times the deposition surface area. Small particle size, high surface area powders can be deposited many layers deep.

Using Electrophoretic Deposition in Electronics Manufacturing

Although not well understood scientifically, EPD has been known as a manufacturing process for well over 70 years. Reference [1] gives a review of some of the manufacturing applications of EPD, while References [2 and 3] cover scientific publications.

The fact that EPD has only rarely been used on a production basis is primarily due to the availability of alternative processes that are both simpler and cheaper. For passive electronic components these technologies have been tape casting and screen printing. For electronic component interconnections the technology has been metal electro-deposition and photolithography. For logic circuits the technology has been thin film photolithography on silicon. Only recently has an opportunity been created for EPD as passive components and interconnect devices shrink to sizes which are not technically feasible by thick film methods and not economically feasible by thin film methods.

The opportunity that we are exploring at Penn State is the potential for the use of EPD in the manufacturing of multilayer ceramic passive components and networks. The objective is to replace the current processes of tape casting, screen printing, and via punch and fill with an alternative which offers photolithographic scale without the extra process steps and expense of performing photolithographic processes on each part.

The current most common production method for these devices is to mechanically cast a continuous particulate tape of a dielectric material. This tape then has via holes punched through it either mechanically or by laser. These holes are refilled with a metal particulate ink by a combination of screen printing and suction. Additional components are added by screen printing particulate inks onto the surface of the particulate tapes. Several tapes are then stacked, laminated and cut to form individual devices. These particulate multilayers are then densified by sintering to form the working device.

The goal of our research is to offer an alternative technology to tape casting where continuous layers need to be less than 2 µm thick and to replace screen printing where patterned components need to have a width less than 30 µm and/or thickness less than 1 µm.

The concept is to create a conductive deposition pattern on a carrier film using standard photolithographic techniques. This conductive pattern can then be coated with particles by EPD. Although particles in a deposition will adhere to each other and to the deposition electrode by van der Waals forces, a binder is introduced to increase the adhesion between the particles and allow them to be laminated to another surface with a greater affinity for the other surface than the deposition electrode. This patterned particulate deposition can then be laminated to the surface of a particulate tape or the top of a laminate stack. The carrier film with the high resolution deposition pattern can then be peeled off and re-used to create a new deposition. In this manner, a single high resolution patterning step, creating a deposition pattern on the carrier by photo/electron beam lithography or laser direct write, can be reproduced in many parts by repeated EPD and lamination steps.

Demonstration

To demonstrate this process a resolution test pattern was created with feature widths down to 1 µm on a 1 µm spacing. This pattern was first imaged as a shadow mask on glass by electron beam lithography at the Penn State Nano-Fab facility. Using U-V photo patterning and sputtering this pattern was transferred to a 125 µm thick polyester film as a 40 nm thick conductive platinum pattern. One component of that pattern, a 5 µm wide serpentine line is shown in Figure 2.

A one micron layer of silver/palladium conductor powder with an average particle size of 300 nm was then deposited onto this pattern by electrophoresis. Complete details of this process are given in Ref. 4. The surface with the deposition pattern was then placed against a pre-cast particulate tape and pressed at 200 MPa and 70° C to laminate the silver palladium particles to the particulate tape. The binder in the pre-cast tape permeated the particulate deposition sufficiently to bond virtually all of the particles to the tape allowing complete transfer of the pattern and clean removal of the patterned deposition carrier film. The results are shown in Figure 3.

Limits to Resolution

The minimum width and spacing for clear, uniform features achieved in this demonstration was 7 µm on a 8 µm spacing. We believe that this is at least an order of magnitude larger than what should be easily possible for this process. The factors limiting resolution in this demon-stration are listed below. Some of these can be addressed easily, the more complex topics are currently under study.

Lateral Growth

As a deposition grows in thickness it will also grow laterally away from the edge of the deposition electrode. In this case it was a deposition pattern of 5 µm on a spacing of 10 µm which, when coated with a 1 µm deposition, grew at the edges to create 7 µm lines on an 8 µm spacing. Any area of the pattern which had spacings less than 2 µm became areas of continuous deposition. This effect can be addressed by simply adjusting the size of the deposition pattern appropriately.

Particle Size in Precast Tape

The deposition was laminated to a DuPont 951-A Low Temperature Cofired Ceramic (LTCC) tape. This tape contains alumina particles up to 5 µm. Therefore at a scale of 5 µm and below the surface of the tape is irregular. This leads to non-uniform transfer of the patterned deposition and discontinuities in features less than 5 µm.

Deposited Particle Size

At 300 nm, the particles being deposited are already a significant fraction of the size of the patterns they are being deposited on. Depositing particles in the 30 to 50 nm range should allow highly uniform imaging of features less than a micron in width.

Figure 2. 5 μm wide serpentine lines on deposition pattern.

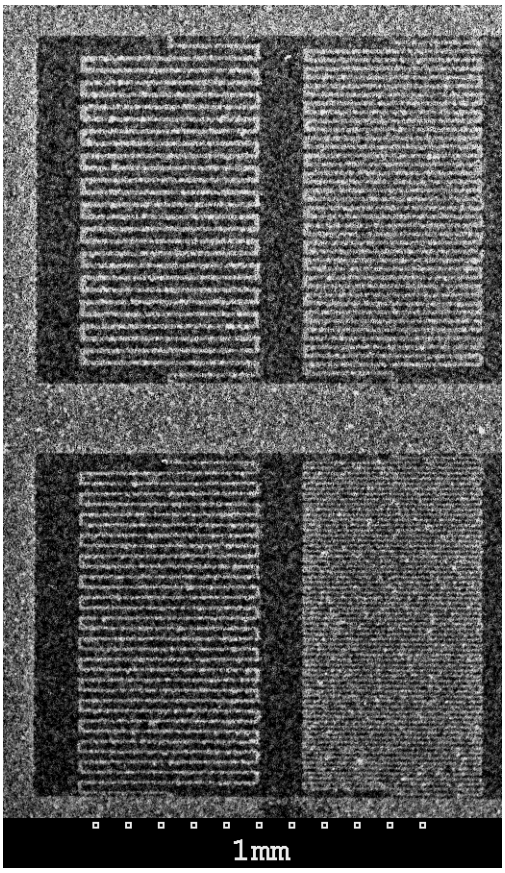

Figure 3. Silver/palladium powder deposited on 10 (top) and 5 μm (bottom) electrode pattern lines and transferred by lamination to a DuPont 951 LTCC particulate tape.

Ramified Growth of Metal Particle Depositions Deposited by the Direct Electrostatic Mechanism

When conductive particles deposit onto an electrode electronic conduction will give the deposited particles the same potential as the electrode. If a deposited particle sticks out from the average surface, electric field lines will concentrate on the higher point, attracting other particles to deposit on that higher point. The more this chain of particles protrudes from the surface the more it will attract other particles, leading to ramified (branched) growth of the deposition away from the surface. This is shown in Fig.4.

The effects of this growth are seen in Fig. 5, where small irregularities are seen at the edges of what are perfectly straight lines on the deposition electrode pattern.

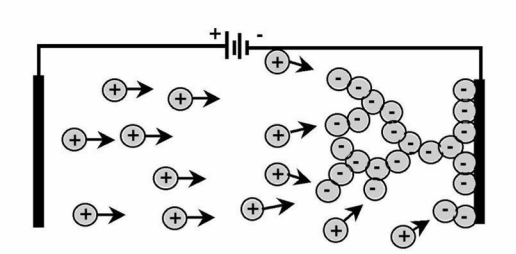

Figure 4. In electrostatic deposition of conductive particles the particles assume the charge of the deposition electrode.

Figure 5. The characters in this optical microscope image were deposited on a pattern made of 20 μm lines and laminated to an LTCC tape.

Current Work

Our current work is focused on dispersion and deposition of metal powders with particles sizes below 100 nm. Using a solvent/polyelectrolyte/electrolyte system the objective is to develop a system that allows for good dispersion of the powder and well controlled deposition as well as minimizing the problem of ramified growth. When this work is completed we expect to be able to demonstrate the reproduction of feature widths of 1 μm and below.

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Acknowledgments

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Biography

Jonathan Van Tassel received a BS degree in Aerospace engineering from The Ohio State Univ. in 1995. Since that time he has been working on EPD at Penn State Univ. where he received his Ph.D. in 2004. He is a three time recipient of the IMAPS student fellowship grant and is a member of sigma gamma tau, the aerospace engineering honor society.