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EME 192 Report

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Professor Farouki

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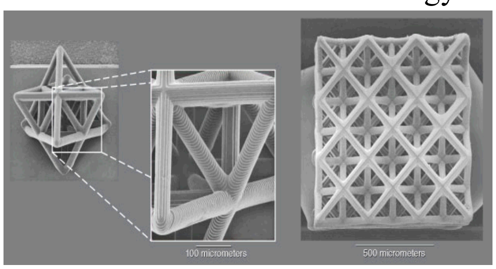
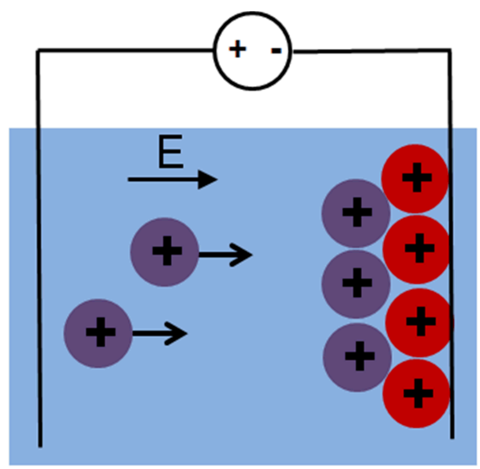
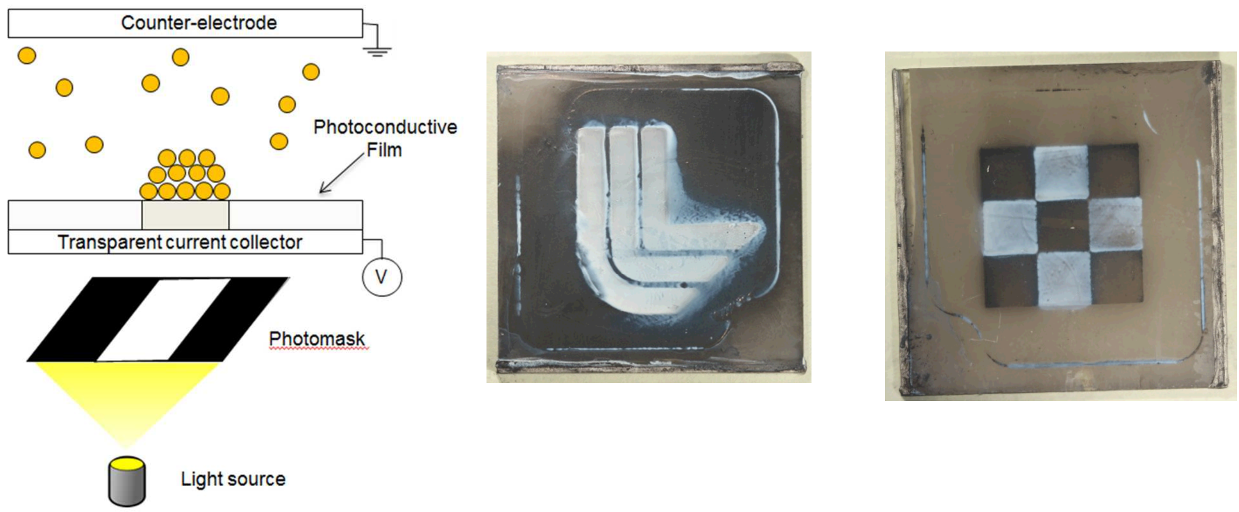
I spent the quarter working in Lawrence Livermore National Laboratory's (LLNL) Materials Engineering Division. The group I have been working with (I've been here for two summers already) focuses on advanced manufacturing techniques such as stereolithography, electrophoretic deposition, and the printing of silicon based inks. Part of the goal of what is done in our group is to create designer materials not by altering the composition but by altering the micro-architecture. Our technology can create shapes that are not possible with traditional manufacturing techniques. This allows us to create structures that are light, yet very strong and stiff. It also allows us to create materials with property gradients. In other words, we can make structures and parts that are stronger in some locations than others. I have been working with electrophoretic deposition for the duration of my stay and have focused on advancing the technology from a thin-film technique to a true additive manufacturing paradigm. Put succinctly, electrophoretic deposition is the deposition of particles in suspension with electric fields. Particles have a potential on the surface which allows them to be driven to an electrode using an electric field. The particles then deposit onto the conductive regions of the substrate, traditionally, the entire surface. Electrophoretic deposition is powerful in that it can handle a wide variety of materials (ceramics, metals, bacteria), create material gradients in the deposits, and create layered deposition of multiple materials. A drawback of *traditional* electrophoretic deposition is that patterned deposits are only possible with a non-reconfigurable patterned electrode. A technique was developed at LLNL that allows for the arbitrary patterning of the electric field using photoconductive electrodes and light. This way, you can create interesting shapes and reconfigure the pattern of the deposit using the same electrode. A photoconductive electrode is made by hydrothermally growing titania nanorods onto a transparent current collector. A photomask is used to block incoming some light and only allow the desired pattern of light through. The photoconductive electrode then activates when and where the light hits, once an electric field is applied. Particles will migrate to the areas of illumation and deposit.





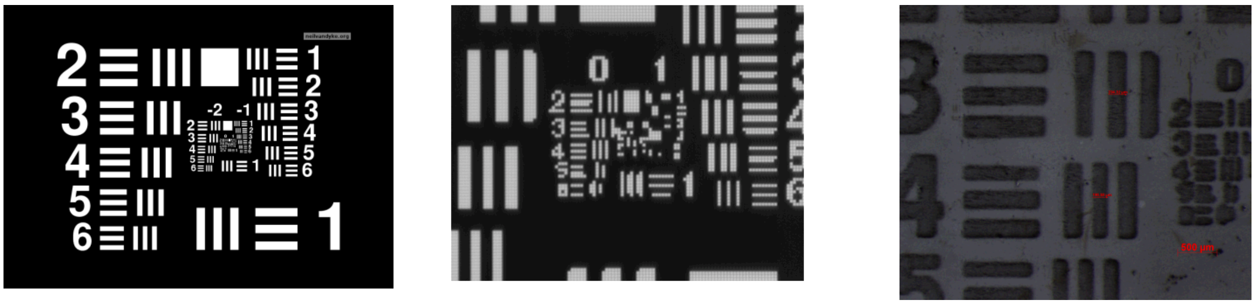


Light Directed Electrophoretic Deposition allows for patterned multi-material deposits.

Some of the work I did the previous summer showed that it is possible to pattern the deposit onto the counter electrode of the system by reversing the polarity of the electric field, such that the material moves toward the counter electrode. This means it is possible to arbitrarily pattern a deposit onto any conductive surface. Shown on the left, is an example of a patterned copper deposit onto an un-patterned piece of aluminum. This is valuable because the photoconductive electrodes are a hassle to grow, and may interfere with any processing that is to be done to the part. I have been working on the next iteration of light directed electrophoretic deposition. It involves doing away with the photomasks and moving to a projector based system instead. Instead of relying on photomasks to create light patterns, a projector can be used to shoot the pattern of interest directly onto the photoconductive electrode. This will allow for dynamic patterning of the substrate and introduces greater freedom for automation of the technique.

An example of the fidelity and complexity that projector based LD-EPD can achieve. A bitmap (left) is the pattern used by the projector to create the deposit (right)

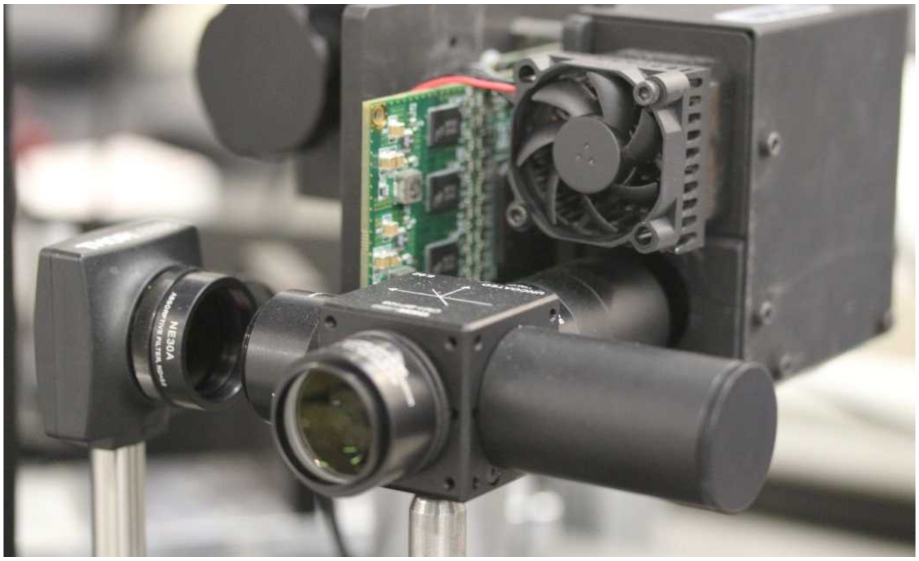
Use of a projector also allows for the creation of certain shapes that were not possible to make before. A photomask is essentially a stencil, which means using one to create a light pattern that has an enclosed feature (i.e. concentric circles) is impossible. As can be seen in the face shaped deposit, this is no longer a limitation. The resolution of light-directed electrophoretic deposition has also been increased. Because the photomasks we used previously were made using a laser, the resolution of the technique is limited by the smallest slit we can cut in the photomask. This results in a minimum feature size of 250 µm. The resolution of projector driven light-directed electrophoretic deposition is less than 100 µm.



An example of a bitmap (left) and deposit (right). The middle image is one captured by a camera that shows what was actually projected onto the substrate.

We are interesting in knowing how well we are reproducing the bitmaps we project. We placed a camera on the focal plane of the deposit and were able to capture the deposition pattern. The camera's pixels have a real size of 5.2 µm x 5.2 µm. This way, we are able to correlate what the deposit should have been to what the deposit actually is. With this particular instance, 1 pixel on the bitmap correlated to 8 pixels on the plane of deposition. A feature with a width of 4 pixels on the bitmap would be 166.4 µm wide. However, when one zooms into the camera image, there is a noticeable blur which is likely due to focusing errors. In the instance above, the total width of the 4 bitmap pixel feature is 44 pixels in camera space as opposed to 32. This results in a theoretical feature size of 228.8 µm, which is virtually identical to the measured feature size of 232.4 µm.

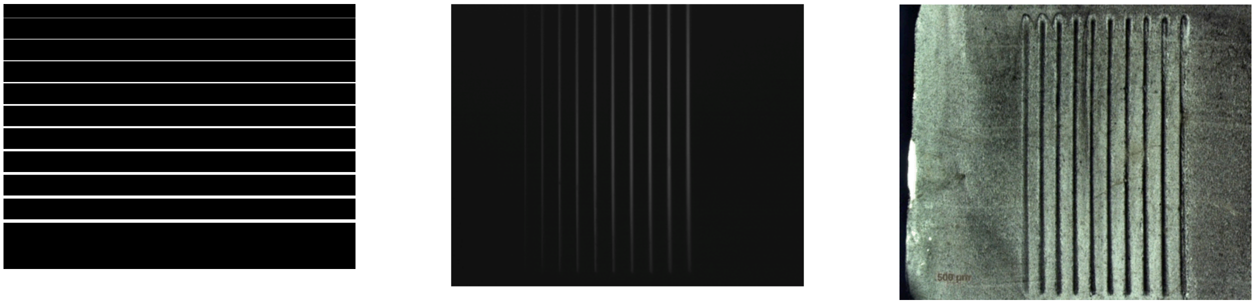
This system is very hard to focus because there is no way to see what is being projected real time. The use of the camera involves moving the camera to the plane of deposition which means that the image cannot be focused on the photoconductive electrode and the camera at the same time. To solve this, a new optics system was developed so that the magnification of the pattern can be changed by switching out a lens, the camera is able to monitor what the image being projected is with little interference, and the image can be focused using fine adjustments on a linear stage.



An image of the new optics system for projector driven light directed electrophoretic deposition.

The optics system is built using basic optical equipment for Thorlabs. It uses achromat doublet lenses to reduce aberrations and to control magnification. There is a pellicle in the middle which takes some of the beam and directs it toward the camera. Light passes through the pellicle and hits the photoconductive substrate. The light then returns and reflects off the pellicle and hits the camera producing an image of what is actually on the substrate. The ratio between the two lenses on either side of the pellicle and the lens just in front of the projector determine the level of magnification. The camera and lenses had to be adjusted spatially so the focal point of the camera and projector is on the same plane as the photoconductive substrate. This is important in being sure that what the camera sees is what is being projected on the substrate and aids in making sure that the image projection is in focus before beginning an electrophoretic deposition experiment.

A question that I tried to answer was what the ultimate resolution of this technique is. For some reason it seems that once the optics were added to the system, the smallest possible feature size got bigger. I had managed to get feature sizes of around 70 to 80 µm without the optics system and now only manage to get 120 µm at most. One of the tests performed was to deposit a set of lines that are equally spaced, yet decrease in width. There were 10 lines and the thickest was 10 pixels. The lines decrease in thickness by 1 pixel down to 1 pixel in thickness. After deposition, the substrate was retrieved and the thickness of all the lines was found to be essentially identical. One would expect the 10 pixel line to be 10 times as thick as the 1 pixel line.

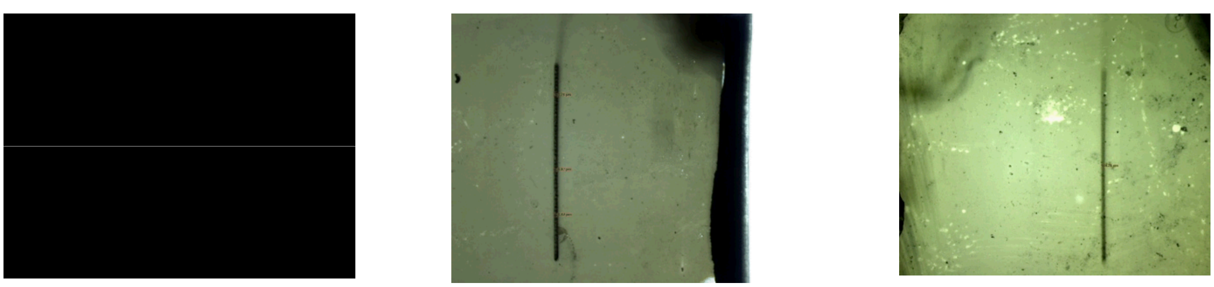


A bitmap (left) and camera image (middle) used to generate the deposition (right).

Shown above is the line test referred to in the previous paragraph. The lines do get marginally thinner as they go from the 10 px line to the 1 px line, but not at the scale one would expect. One avenue we explored was to reduce the time of deposition. All deposits shown up until this point were performed for 30 seconds. Shown below are two deposits at 20 seconds and 5 seconds. The lines are still approximately the same width, only a little less material has been deposited. The 20 second deposit appears to have the best distinction between line thicknesses, but the 10 pixel line is still nowhere near 10 times as wide as the 1 pixel line (It's only a factor of about 2). We aren't really sure why the lines all have the same thickness, but we believe that it is because we have reduced the size of our image with the optics system but we have not reduced the incoming light intensity. This causes extra regions of illumination and thus, conductivity.

Equally spaced line test deposit performed for 20 second (left) and 5 seconds (right).

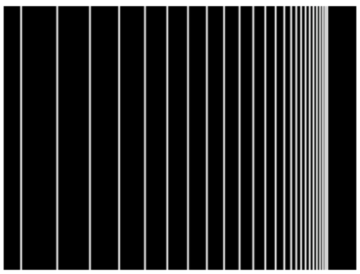
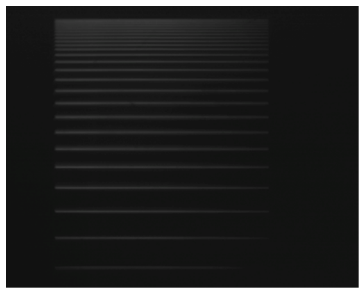
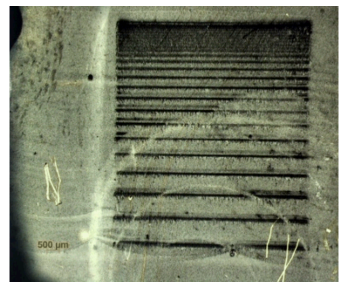
In order to find the ultimate resolution of this technique, a one pixel line was projected onto the substrate in the hope that the other lines that may have been interfering will not. A 1 pixel line is the thinnest object we can project, so this should give us the thinnest object we can produce.



The 1 pixel bitmap (left) used to deposit a line. 30 second (middle); 5 seconds (right)

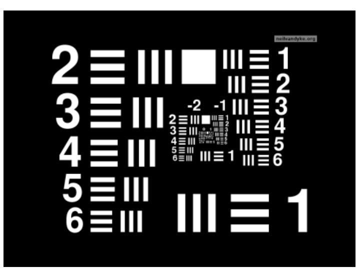
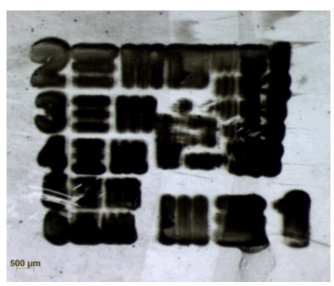
The 30 second deposit for the one pixel line was at its thinnest point 184 µm thick. The 5 second deposit was 164 µm at its thinnest point. Tests to reduce the light intensity before deposition have not been attempted, so we still are unsure if that is why the features are not as fine as they could be. Attempts to further reduce the feature size were done by reducing the magnification by 2. This resulted in a shorter line, with roughly the same width as the above two images. Future experiments will attempt to reduce the feature size by changing light intensity.

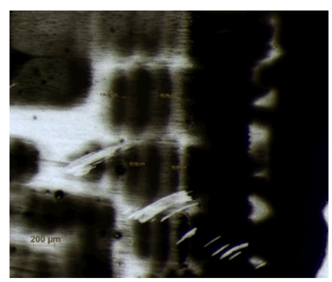
The following will be a summary of a few depositions that were performed. In addition to the line width tests, a test was performed on how closely lines could get before they cannot be distinguished. The lines all have the same 5 px thickness, however the spacing between them decreases as more liens are added until there is a 1 px spacing between the two last lines. Analysis has not been done on the ultimate spatial resolution, but the results can be seen below.

Line spacing test. Bitmap (left) and camera image (middle) for the deposit (right).

The first deposit to be performed with the new optics system was the air force target typically used for microscope calibration. It didn't go as well as the deposit without the optics system likely due to light intensity issues. There is also a lot of detail that is going into a very small area (less than half one square inch). This leads to a lot of spacing issues because the spatial resolution of this technique at this magnification could be better.



Bitmap (left) of the deposit (middle). Spacing issues are made apparent in the right image.

An early projector driven light directed electrophoretic deposition piece is seen below. Its purpose was to demonstrate the capability to deposit enclosed features (which was not previously possible with the photomask technique).