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Novel Low Pressure Sputtering Source and Improved Vacuum Deposition of Small Patterned Features Using Precision Shadow Masks

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ABSTRACT

A novel low-pressure sputtering source (LPSS) has been successfully used to deposit crisp, well-defined 10- μm -and-larger features using precision shadow masks. The LPSS operates at low pressure yielding viable deposition rates and low thermal exposure of the mask and allows sputter deposition from both the top and bottom cathode surfaces. The LPSS design has been scaled to a large area 6" $\times$ 32" source that enables efficient additive manufacturing of embedded electronic devices, circuits, and systems using precision shadow masks.

INTRODUCTION: A NOVEL SPUTTERING SOURCE TECHNOLOGY

This paper reports on the collaborative work of Advantech U.S., Inc., and the Kurt J. Lesker Company on a novel thin-film deposition technology for embedded electronic components and circuits. The novel low-pressure sputtering source (LPSS) is suitable for deposition of fine-pattern thin films using precision shadow masks.

TODAY'S SHADOW MASK TECHNOLOGY

Deposition of thin films through precision shadow masks bridges a highly desired feature size range for electronic devices and components. The traditional integrated circuit (IC) manufacturing industry typically patterns device features from 1 μm down into the nanometer range. The printed circuit board (PCB) industry works with feature sizes from 50 μm (2 mils = 0.002") to hundreds of millimeters.

Both the IC and PCB industries use photolithography – on different length scales – and subtractive processing steps to pattern their substrates.

In contrast, the evaporative printing process developed by Advantech enables complete additive manufacturing of electronic devices and circuits with feature sizes and spacing between 5 μm and several cm, bridging the feature size gap between the IC and the PCB manufacturing industries (Figure 1). Fine line interconnects, interposers, vias, passive embedded devices such as resistors, parallel plate capacitors, gap filters, inductors, antennas, and so on, as well as MOSFETs, logic gates, and active matrix display backplanes have been built with this technique. The process uses an in-line multi-chamber vacuum deposition system. No wet chemical process steps are required in the device deposition or patterning operations. The evaporation printing process deposits thin films with near-bulk material properties and performance using physical vapor deposition on a wide variety of substrates – display-grade rigid or flexible glass, advanced circuit board substrates, plastic or metal foils. The resulting devices, circuits, and board layers can be used directly in traditional PCB lamination, bonding, or solder processes.

THIN FILM DEPOSITION THROUGH SHADOW MASKS

Figure 2 depicts the arrangement for physical vapor deposition (PVD) of patterned thin films through a shadow mask in a vacuum deposition system.

The thin film material originates at the source and is turned into a vapor flux using a thermal evaporator, an e-beam evaporator, or a sputter source inside a vacuum chamber. The substrate opposes the material source at a distance T above the source. A shadow mask is placed parallel to the substrate facing the materials source, aligned to the substrate, and brought into close contact with the substrate.

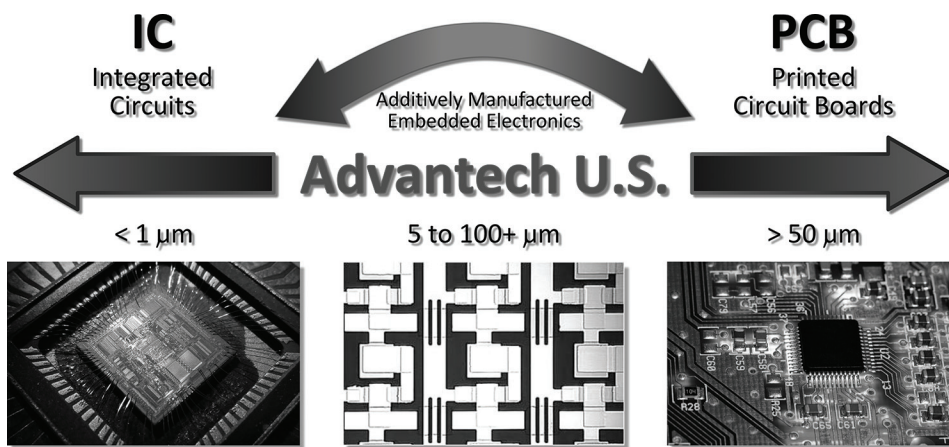


Figure 1. Bridging The Gap – Typical feature sizes in integrated circuit manufacturing, evaporation printing, and printed circuit board technology.

Physical Vapor Deposition Through Shadow Mask

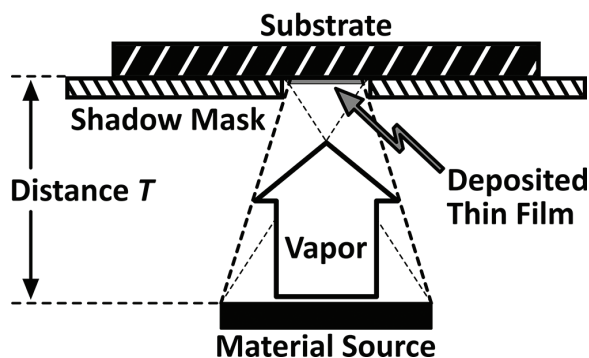


Figure 2. Physical vapor deposition (PVD) through a shadow mask in line-of-sight conditions.

Precision shadow masks, also referred to as “Fine Metal Masks (FMM),” are made from a thin foil such as nickel or stainless steel. Typical foil thickness ranges from 10 to 25

μm . Small openings or apertures are created through chemical or laser etching. For highest resolution the foil is made by an electroforming process. The aperture pattern is first produced using a photoresist exposure process, where resist is left on the forming mandrel in any area that forms an aperture. Aperture dimensions of $10 \mu\text{m}$ and less have been produced reliably using this method. (Figure 3).

The shadow masks are mounted on rigid mask frames designed for the automated mask storage, handling, and alignment system. Positional accuracy of the shadow mask is verified prior to and during the mounting process using a vision measurement machine (VMM).

In the deposition process the mask is first placed between the evaporation source and the substrate. Advantech uses a high precision alignment system to align the mask to fiducial marker patterns on the substrate and places the mask within $1 \mu\text{m}$ of its desired position. This allows the use of multiple masks to create complex patterns and/or deposit different materials to build complete electronic circuits.

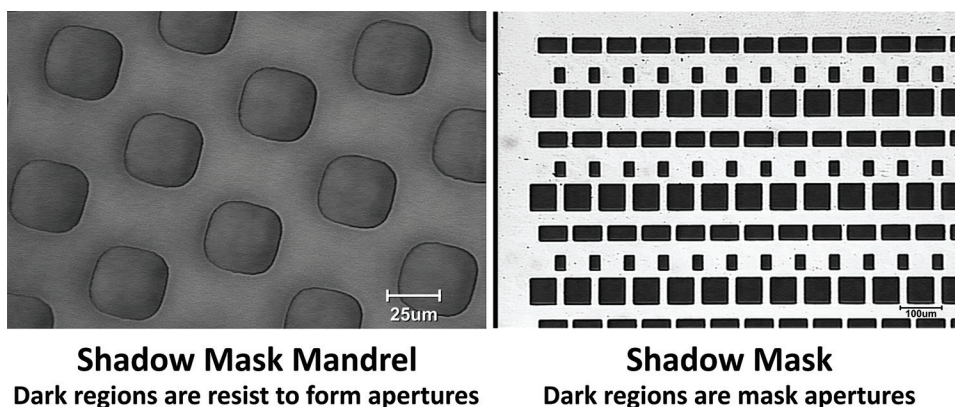


Figure 3. Shadow mask mandrel (left) and electroformed nickel shadow mask (right).

After alignment the mask is brought into direct contact with the substrate to avoid any shadowing effect (also described as overspray). When magnetic materials are used for the mask, such as nickel foil, a magnet behind the substrate can enhance the contact between mask and substrate.

The desired material is then deposited onto the substrate/mask combination. After the deposition process is completed and the mask is removed the desired pattern remains on the substrate.

SHADOW MASKS LIMITATIONS: THERMAL EXPANSION

A critical factor determining the geometrical precision of the deposited thin film pattern is the position accuracy of the shadow mask relative to the substrate during the duration of the deposition process. In particular, heat imposed by the material source on the shadow mask and substrate can result in poor quality of the deposited features.

The shadow mask material is subject to thermal expansion when exposed to heat from the deposition source. Absolute positions of the aperture patterns relative to the substrate will deviate from the desired deposition locations due to thermal expansion of the mask material and mask frame. Positions of apertures relative to each other on the mask are likewise affected by thermal expansion and the method of mounting the shadow mask on the frame, as well as the method of mounting the mask and frame relative to the substrate. Similarly, the substrate experiences thermal expansion by heating imposed by the material source. These thermal mask expansion effects result in a positional offset of the deposition pattern from the desired deposition position, often compromising the device's functionality.

Besides dimensional instability thermal expansion can also lead to buckling and unintended separation between mask and substrate. Any separation between mask and substrate leads to shadow deposits or overspray, as illustrated in Figure 4.

Thermal management therefore is essential to prevent any of the aforementioned shortcomings. Pre-stressing the mask, for example, allows for some compensation of heat-up, as does proper timing of the deposition sequence.

REQUIREMENTS FOR HIGH DEFINITION OF FINE FEATURES

PVD occurs in a vacuum vessel that is typically evacuated to a base pressure low enough to enable vapor species trans-

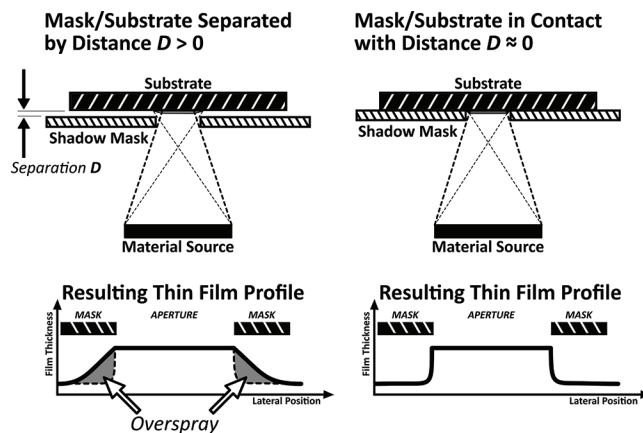


Figure 4. Thin film height profile for deposition with shadow mask separated by distance D from substrate (left) and shadow mask in close contact with substrate (right).

port with a mean free path λ exceeding the source/substrate distance $T > \lambda$. Under such conditions, the vapor path between the source and the substrate approximates line-of-sight conditions, indicated by the dashed lines in Figure 4. For a base pressure of 1×10^{-3} Pa the mean free path is approximately 50 m, significantly larger than the source/substrate distance T .

Generally, physical vapor deposition (PVD) by evaporation is suitable for producing sharp, well-defined features in thin films deposited through ideal shadow masks. This is the case in particular if the source resembles a point source such as thermal or e-beam evaporator at an appropriate distance from the mask/substrate arrangement and the base pressure can be held below 1×10^{-2} Pa.

A difficulty for evaporation processes lies in the limitation of size for the source as well as the selection of materials that can be evaporated from either thermal or e-beam sources. Some refractory metals, for example, require fairly high evaporation temperatures. The undesired side effect of evaporation at such high temperatures is the heat transfer generated by radiation.

SPUTTER DEPOSITION THROUGH SHADOW MASK

Sputtering offers an enhanced selection of materials that can be vacuum deposited as thin films on many types of substrates. Traditional sputter deposition, however, requires a chamber pressure of 1 to 10 Pa or even higher. In this pressure range the mean free path of sputter species is reduced to 0.05 m and less. For shadow mask deposition, however, it is impossible to place a sputter source this close to the mask

to achieve more or less line-of-sight deposition and creation of sharp and defined features. The close proximity results in a coupling of the sputter plasma into the metal mask, and the electron current into the mask creates an unacceptable heat load in the mask, resulting in the aforementioned problems.

Increasing the distance between sputter source and mask and the reduced mean free path in this pressure regime results in frequent gas phase collisions of the sputtered vapor and the ambient gas molecules, and this creates non-line-of-sight deposition conditions. Patterns deposited by conventional sputtering through a shadow mask are broadened and blurred compared to evaporative physical vapor deposition (Figure 5).

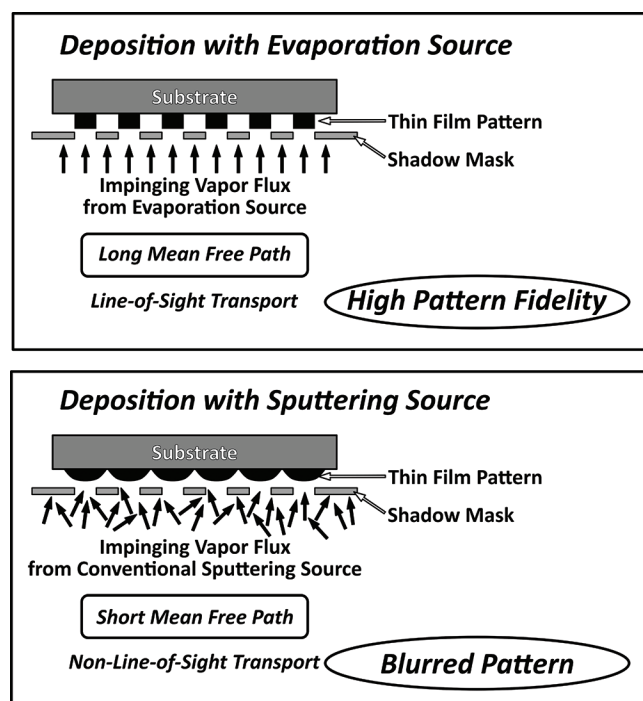


Figure 5. Evaporation (top) and conventional sputter deposition (bottom) through shadow mask and resulting feature height profiles.

RESULTS: LOW-PRESSURE SPUTTERING SOURCE

Advantech U.S., Inc., employed a novel low-pressure sputtering source (LPSS) developed by the Kurt J. Lesker Company that sustains stable operation at a pressure as low as 0.01 Pa (7.5×10^{-5} Torr).

The low pressure operation results in an increase of the mean free path to about 0.5 m, which allows sufficient separation between mask and sputter source to prevent coupling of plasma into the metal mask.

Figure 6 shows a top view and side view of the first-generation prototype of the LPSS. The horizontally mounted aluminum (AL) cathode body holds three integrated rod magnets and water cooling lines. The magnetic field lines wrap around the entire cathode body, creating an electron race track around the entire source. The LPSS source sputters material from both the top and bottom surfaces, consuming the cathode body.

Low Pressure Sputtering Source (Generation 1)

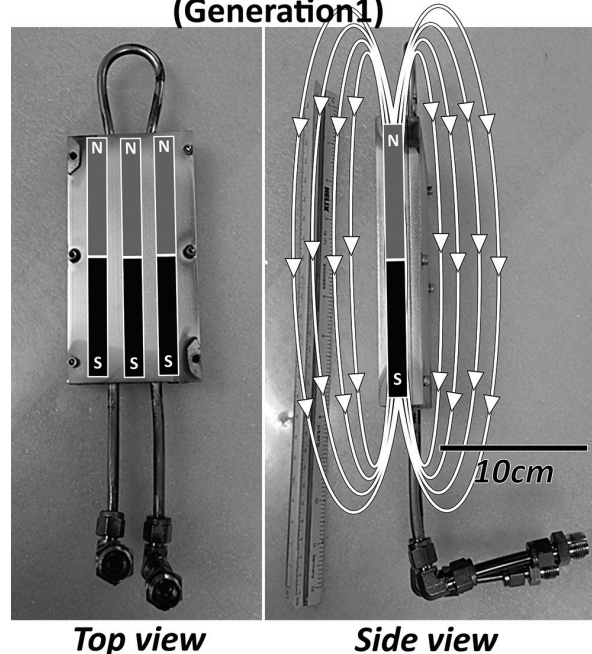


Figure 6. Low-pressure sputtering source Gen 1 prototype 8.9 cm $\times$ 19 cm (3.5" $\times$ 7.5") with magnet arrangement.

Figure 7 shows the voltage over pressure curve of a conventional magnetron sputtering source (triangle symbols on dashed curve) compared to the LPSS (circle symbols on solid line).

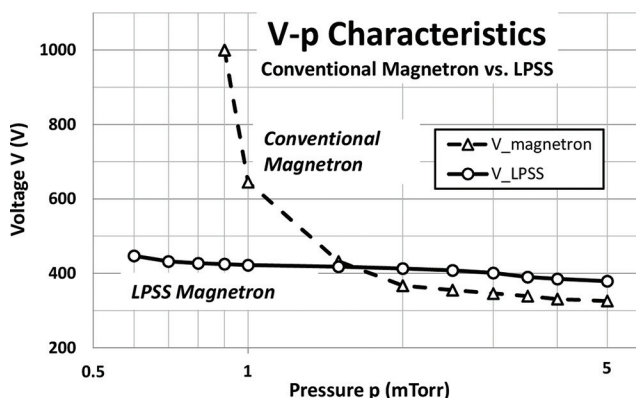


Figure 7. Voltage-pressure curves for conventional (dashed lines) and LPSS sputtering source (solid lines). The LPSS exhibits its stable operation pressures below 12 Pa (1 mTorr) similar to cylindrical post magnetron sources [1]

solid curve). Transport rates achieved with the LPSS are comparable to conventional sputtering sources. The LPSS achieves power densities that exceed those of conventional sputtering sources by one or two orders of magnitude. The original Gen 1 LPSS prototype was sized 8.9 cm × 19 cm (3.5" × 7.5") (Figure 6), the second-generation LPSS features 15.2 cm × 40.6 cm (6" × 16") and 15.2 cm × 81.3 cm (6" × 32") cathodes for large area deposition (Figure 8). The Gen 2 LPSS cathodes are mounted on a linear scanning stage to accommodate deposition on substrates as large as 61 cm × 91 cm (24" × 36").

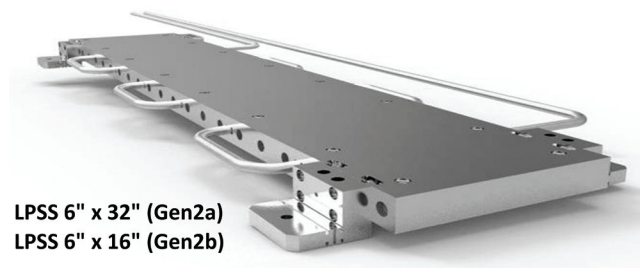


Figure 8. Second-generation large-area low-pressure sputtering source (LPSS) with 40.6 cm (16") and 81.3 cm (32") (shown) length.

MASKED THIN FILM DEPOSITION RESULTS USING NOVEL LOW-PRESSURE SPUTTERING SOURCE

Figure 9 shows the height profiles (lower graph) of 100-μm-wide features deposited through the same 20-μm-thick shadow mask using a conventional magnetron sputtering source (solid grey profile) and the Gen 1 LPSS in stationary mode (dashed black profile), both with 15.2 cm (6") target-substrate distance. The two upper images in Figure 9 are shadow masks with 60-μm and 70-μm features. LPSS deposition of the 800-Å-thick film from an aluminum target occurred at a chamber base pressure of 1×10^{-3} Pa and sputter pressure of 0.28 Pa under 2.5 sccm Ar flow with a DC power of 37 W at 467 V with a 15 min deposition duration. The LPSS-sputtered features replicate the mask aperture dimensions, whereas the features deposited with the conventional magnetron source exhibit a rounded profile that does not entirely fill the width of the 100-μm-wide shadow mask aperture.

Figure 10 shows a pattern of 10-μm-wide features deposited through a shadow mask with the 40.6 cm (16") Gen 2 LPSS source at 16.5 cm (6.5") target-substrate distance. The height profile of the features are crisp and well defined. It is worth noting that the profile was acquired with a 12.5-μm stylus which created to the rounded top edge shape.

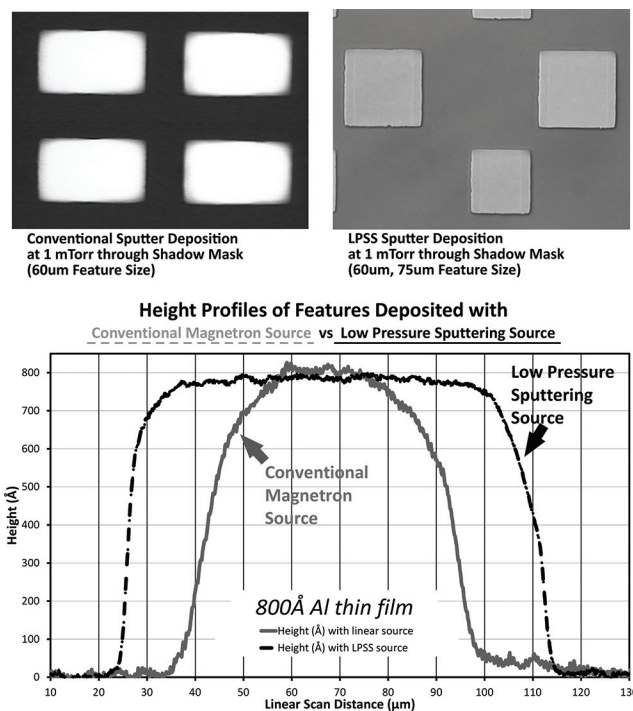


Figure 9. Shown in the lower graph is a comparison of 100-μm features and their height profiles deposited by two different sources. One profile was deposited with a conventional sputtering source (grey solid line); the other profile was deposited by the Gen 1 LPSS (black dashed line). The LPSS deposition shows a sharper, more well-defined deposited feature as compared to conventional sputtering. The upper images in this figure are of 60 μm, 70 μm feature shadow masks.

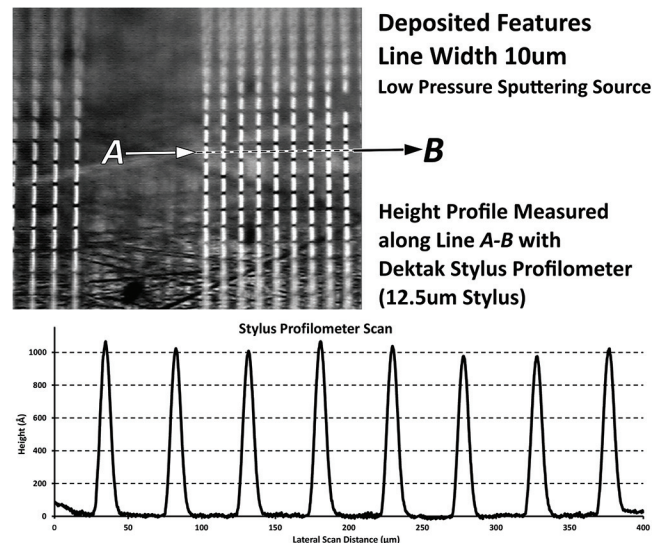


Figure 10. Height profile of 10 μm features deposited with LPSS through a shadow mask. The top image shows the deposited pattern. The bottom graph shows the surface profilometer scan from A to B, using a 12.5 μm stylus. The LPSS deposition yields sharp, well-defined features.

CONCLUSIONS

The novel low-pressure sputtering source (LPSS) has been successfully used to deposit crisp, well-defined 10- μ m-and-larger features using precision shadow masks. The LPSS operates at low pressure yielding viable deposition rates and low thermal exposure of the mask and allows sputter deposition from both the top and bottom surfaces.

The 17.8 cm (7") LPSS prototype was scaled to 40.6 cm (16") and 81.3 cm (32") and succeeded in low pressure operation and deposition of sharp, well-defined features in stationary and scanning conditions. To date, aluminum, copper, and several refractory metals have been successfully deposited with the LPSS sources.

A patent application has been filed, and a production-ready cathode design is being evaluated while the source material portfolio is expanded.

The cost- and process-efficient LPSS technology opens new avenues for the additive manufacture of embedded electronic devices, circuits, and systems patterned by shadow masks, using advanced thin film materials.

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