# Micrometer-resolution color printing via room-temperature, photochemical deposition of metallic structures

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Micro- and nanostructured metal thin films are critical components for various devices including advanced microelectronics, photonics, sensors, and many more. Conventional fabrication typically involves cleanroom-based lithography and vacuum deposition, which are costly, time-consuming, and inaccessible to many users. Additive manufacturing, such as Digital Light Processing (DLP), combines multiple steps into simplified workflow in ambient condition for scalable and maskless production. However, the resolution of DLP is limited due to the incoherent nature of the projected light[1]. Here, we report a relay-optics-enhanced DLP (DLP-relay) (Figure 1) based polymer-assisted photochemical (PPD) deposition[1] of metallic thin films and demonstrate its use in color display. DLP-projected UV light is focused via relay lens to illuminate metal precursor, inducing photochemical reduction of metal ions into metal nanoparticles, which are subsequently connected into continuous metal films. Previously we demonstrated a minimum printed linewidths of 6.5µm for color printing, and here we show that the enhanced relay optics system further enhanced the resolution, allowing printing features as small as 1.3µm (~ 0.5 µm/pixel)[2] (Figure 1).

We found that the printing quality is highly dependent on focusing. As an example, line width of 6.4±0.6 µm was achieved for 2 px gratings when printed in focus (at stage height reference Z= -110 µm), while the linewidth worsened to 12.2±0.7 µm off focus (Z=-100 µm). Understandably, line thickness also grew faster when focused compared to off-focus printing (Figure 2). In addition, time dependent film-growth study revealed three stages of metal growth, where the initial nucleation dependent seeding was followed by a faster kinetically drive growth and finally slower diffusion limited growth (Figure 2). The new system supported high-resolution structural color using Fabry–Pérot cavity structures. Grayscale-modulated DLP exposure enables spatial control of metal film thickness, producing vivid multicolor images with feature sizes down to 1.3 µm in a single printing step (Figure 3). Measured reflectance spectra and CIE chromaticity coordinates of the printed structures are in accordance with simulated spectra by FDTD, Lumerical (Figure 3). This work demonstrates DLP-relay PPD as a powerful, low-cost, and scalable approach for micrometers- and sub-two-micrometer-scale metal printing, with implications for high-resolution imaging, photonic devices, metasurfaces, sensors, and advanced colorimetric technologies.

Reference:

1 Z. Zhao, J. Bai, Y. Yao and C. Wang, Materials Today, 2020, 37, 10–17.
2 S. Choi, Z. Zhao, …Y. Yao and C. Wang, Light Sci Appl, 2022, 11, 84.

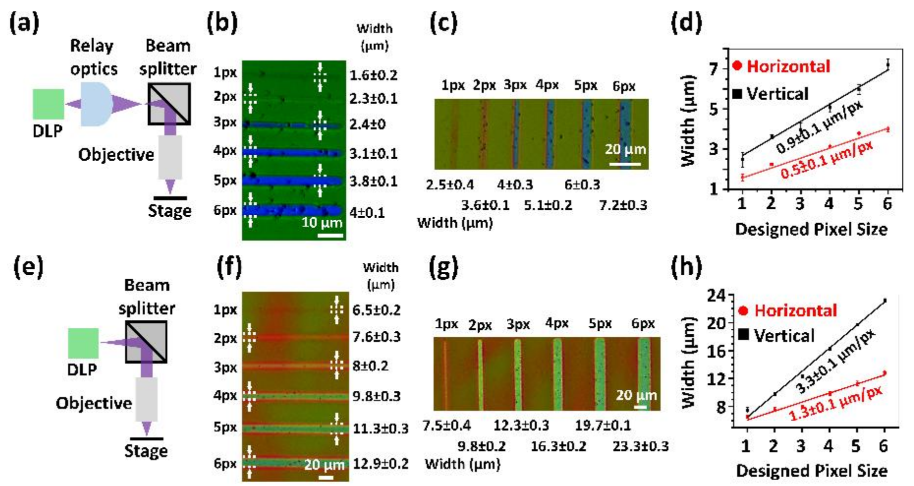


**Figure 1: Characterization of printed structure:**(a-d) Printing with DLP-relay: (a) Schematic; (b-c) Optical images of PPD Ag lines along (b) horizontal and, (c) vertical orientations, (d) Pixel size plotted against line width. (e-h) Printing with DLP only: (e) Schematic; (f-g) Optical images of PPD Ag lines along (f) horizonal and (g) vertical orientations, (h) Pixel size plotted against line width.

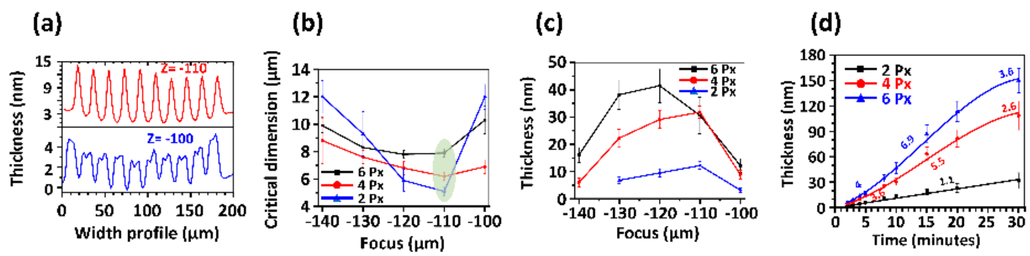


**Figure 2: Focus optimization and time dependent printing:** (a) Width vs Thickness profile of 2 Px gratings, (b) Focus Vs critical dimensions, (c) Focus vs thickness profile, (d) Grating thickness vs printing time.

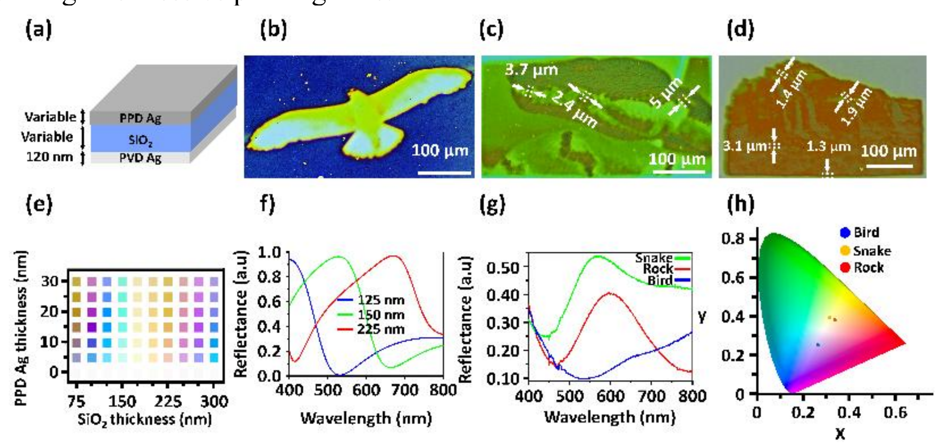


**Figure 3: Multicolor structural printing:** (a) 3D schematic Fabry-Pérot cavity structure; (b-d) PPD Ag-printed structure on a $SiO_2$/Ag/Ti/Si substrate: (b) yellowish bird in blue sky, (c) green snake, and (d) red-yellowish mountain, (e) Simulated color map as function of mid spacer layer (SiO2) and top reflectance layer (PPD Ag) thickness, (f) Simulated reflectance spectra within 400-800 nm wavelength range, (g) Reflectance spectra of printed structure at 400-800 nm wavelength of light, (h) 1931 CIE color coordinates of the printed structure extracted from reflectance spectra.