Visualization of ultra-thin semi-transparent metallic films by wave simulations and ray-tracing rendering

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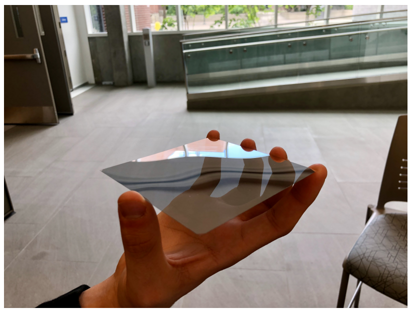
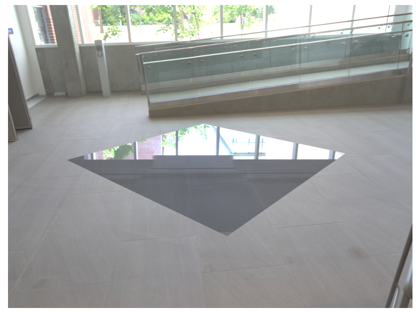


(a) Real, fabricated silver thin film



(b) Rendered silver thin film

Figure 1: Physical appearance of a 20-nm-thick film of silver deposited on a 100-micron-thick glass substrate that is 1(a) fabricated and photographed adjacent to a window on a cloudy day using an iPhone X back dual camera and 1(b) rendered with Substance Designer software using material parameters derived from electromagnetic wave simulations.

CCS CONCEPTS

• **Nano-structure visualization** → **Ray tracing rendering**; *plasmonic color*; FDTD; • **FDTD simulation** → ray tracing rendering.

KEYWORDS

plasmonic color generation, FDTD, nano thin film, rendering

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1 INTRODUCTION

Plasmonic color generation describes structural color arising from resonant interaction between visible light and metallic nanostructures, causing selective frequencies of light to be scattered and/or absorbed [Kristensen et al. 2017; Sun and Xia 2003]. The perceived color from such metallic nanostructures is highly dependent on viewing angle and the color appearance can change with color of the viewing background. Plasmonic color generation is a rapidly emerging research area with potential advantages over conventional pigment printing technology including higher printing resolution and robustness, greater compatibility for integration and functionalization, and reduced resource requirements [Mudachathi and Tanaka 2017; Zhu et al. 2017]. Structural color from plasmonic nanostructures has already been used to improve security measures in currency notes and credit cards [Lee et al. 2018].

Achieving desired structural coloration using nanostructures requires bottom-up design in which the electromagnetic properties of nanostructures are simulated and then extrapolated to model their visual appearance. Computer graphics technology can be used to provide visualization of the optical properties of nanostructures on large scales [Auzinger et al. 2018; Musbach et al. 2013; Zhu et al. 2009]. In this work, we propose to use finite-difference time-domain (FDTD) simulations to model electromagnetic interaction of visible light with nanostructures and create physical-based material models to visualize their appearance by ray-tracing rendering.

2 OUR APPROACH

The goal is to visually match the appearance of a nanofabricated film by ray-tracing rendering. We use a 20-nm-thick silver thin film deposited on 100-micron thick glass substrate as an initial case study. The fabricated film is not perfectly smooth. We model the nanoscale surface roughness of the 20-nm-thick silver film with a randomize function based on the surface correlation function

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$$\langle H(r)H(r+\delta)\rangle = \sigma^2 e^{-\left(\frac{\delta}{L_c}\right)^2} \quad (1)$$

where $H(r)$ is surface height at the position r, σ is average roof mean square (RMS) amplitude, δ is sampling resolution of the surface, and L_c is correlation length of roughness in the x and y directions[Zhao et al. 1998]. We use FDTD simulations, as opposed to the transfer matrix method, to incorporate effect of roughness which produce diffuse reflection. We model the time-averaged electromagnetic wave amplitudes that are transmitted and reflected from the silver-coated substrate under plane-wave continuous-wave illumination at normal incidence.

We define a 4 μm × 4 μm glass substrate coated on its top side by a 20-nm-thick silver thin film with roughness parameters as:

Table 1: Surface roughness parameters

Variables	Values
RMS amplitude, σ	19 nm
Sampling resolution of the surface, δ	4 nm
Correction length of roughness	
x direction	2 nm
y direction	2 nm

Due to symmetry, the simulations are conducted over a 2D region with dimensions of 300 nm × 300 nm. The horizontal boundaries of the simulation space have periodic Bloch boundary conditions. The vertical boundaries of the simulation space have perfectly matched layers (PMLs), which perfectly absorb both transmitted and reflected light. The light source is a plane wave and it is positioned 2 μm above the substrate.

To create a physical based material model of the 20-nm-thick silver thin film for rendering, we use the material definition language (MDL) in Substance Designer. Since the 20-nm-thick silver is semi-translucent, both reflectance and transmittance are needed to model its optical properties accurately. RGB value of reflectance and transmittance for silver film are calculated using CIE XYZ 1931 color system transformation with a standard D65 illuminant [Ford and Roberts 1998]. Nanoscale roughness of the silver film described by the surface roughness correlation function exists on top of microscale roughness described by microfacet GGX. Direct use of the Fresnel reflectance in rendering becomes more complicated as refractive index values are needed over the visible spectrum and these values may be complex. Under these conditions, Schlick introduced an approximation of Fresnel reflectance as

$$F(\mathbf{n}, \mathbf{l}) \approx F_0 + (1 - F_0)(1 - (\mathbf{n}.\mathbf{l})^5 \quad (2)$$

where $\mathbf{n}$ is the surface normal vector and $\mathbf{l}$ is the incoming direction vector [Schlick 1994; **?**].

Figure 1(a) is a photograph taken from iPhone X's back camera of a 4" × 4" glass substrate coated with a 20-nm-thick silver thin film prepared by magneton sputter deposition (Angstrom Engineering Nexdep). Figure 1(b) is a rendered image of the same coated substrate using 360 HDR environment lighting on Nvidia iray rendering engine in Substance Designer software. Both images of the coated substrate in Figure 1 are captured at a tilted angle, highlighting reflectivity and semi-transparency of the sample. The color-matched sRGB transmittance of the silver-coated thin film is gray blueish in color. Both the real image and the rendered image show a glossy finish with gray blueish color.

3 CONCLUSION AND FUTURE WORK

This work demonstrates the feasibility of rendering the physical appearance of semi-transparent nano-scale metallic films by combining electromagnetic simulations with ray-tracing-based rendering. Electromagnetic simulations enable detailed modelling light interaction with nano-scale features (in this case, the surface roughness of the film). Future work will study the rendered appearance of more complicated nanostructured metallic media for applications in plasmonic colour generation.

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