

Crafting ultrathin color coatings: Physicists produce vivid optical effects—on paper

December 22 2014, by Caroline Perry



Behind the scenes in the Center for Nanoscale Systems, Mikhail Kats (Ph.D. '14) demonstrates the fabrication process for ultrathin coatings that shine in vivid colors. Kats and Prof. Federico Capasso have shown that these interference effects work on rough materials like paper. Credit: Eliza Grinnell

In a sub-basement deep below the Laboratory for Integrated Science and Engineering at Harvard University, Mikhail Kats gets dressed. Mesh shoe covers, a face mask, a hair net, a pale gray jumpsuit, knee-high fabric boots, vinyl gloves, safety goggles, and a hood with clasps at the

collar—these are not to protect him, Kats explains, but to protect the delicate equipment and materials inside the cleanroom.

While earning his Ph.D. in [applied physics](#) at the Harvard School of Engineering and Applied Sciences, Kats has spent countless hours in this cutting-edge facility. With his adviser, Federico Capasso, the Robert L. Wallace Professor of Applied Physics and Vinton Hayes Senior Research Fellow in Electrical Engineering, Kats has contributed to some stunning advances.

One is a metamaterial that absorbs 99.75 percent of infrared light—very useful for thermal imaging devices. Another is an ultrathin, flat lens that focuses light without imparting the distortions of conventional lenses. And the team has produced vortex beams, light beams that resemble a corkscrew, that could help communications companies transmit more data over limited bandwidth.

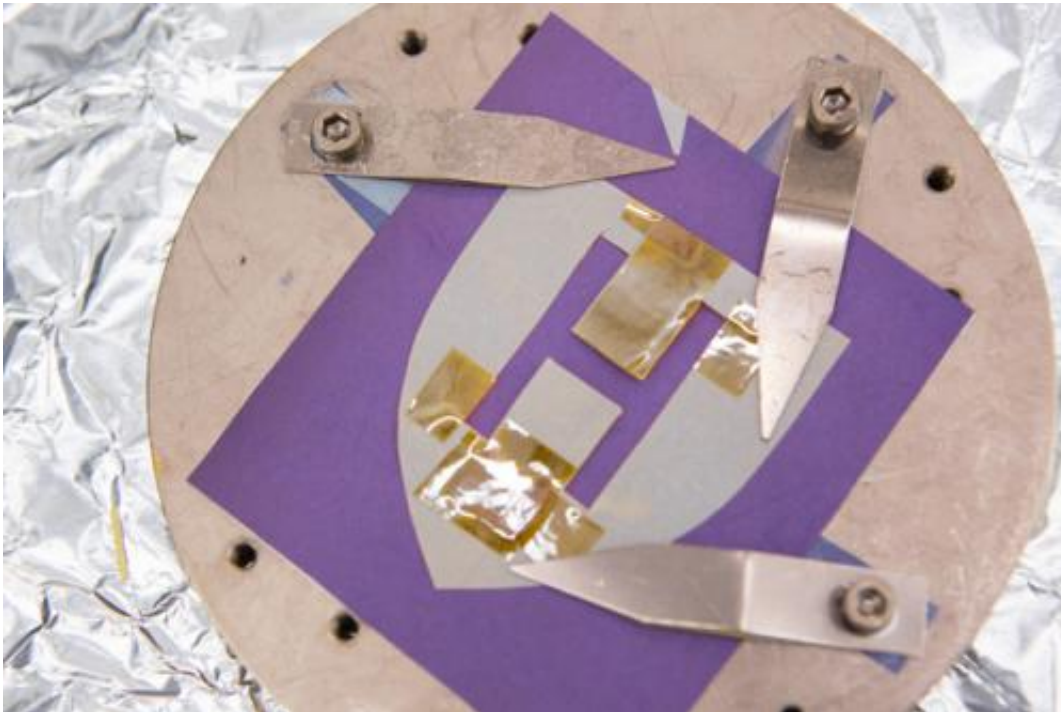
Certainly the most colorful advance to emerge from the Capasso lab, however, is a technique that coats a metallic object with an extremely thin layer of semiconductor, just a few nanometers thick. Although the semiconductor is a steely gray color, the object ends up shining in vibrant hues. That's because the coating exploits [interference effects](#) in the thin films; Kats compares it to the iridescent rainbows that are visible when oil floats on water. Carefully tuned in the laboratory, these coatings can produce a bright, solid pink—or, say, a vivid blue—using the same two metals, applied with only a few atoms' difference in thickness.

Capasso's research group announced the finding in 2012, but at that time, they had only demonstrated the coating on relatively smooth, flat surfaces like silicon. This fall, the group published a second paper, in the journal *Applied Physics Letters*, taking the work much further.

"I cut a piece of paper out of my notebook and deposited gold and germanium on it," Kats says, "and it worked just the same."

That finding, deceptively simple given the physics involved, now suggests that the ultrathin coatings could be applied to essentially any rough or flexible material, from wearable fabrics to stretchable electronics.

"This can be viewed as a way of coloring almost any object while using just a tiny amount of material," Capasso says.



The sample, fresh out of the chamber. The paper stencil has turned gray, the natural color of germanium. But where the germanium has landed on the gold-coated paper, the color is violet. Credit: Eliza Grinnell

It was not obvious that the same color effects would be visible on rough

substrates, because interference effects are usually highly sensitive to the angle of light. And on a sheet of paper, Kats explains, "There are hills and valleys and fibers and little things sticking out—that's why you can't see your reflection in it. The light scatters."

On the other hand, the applied films are so extremely thin that they interact with light almost instantaneously, so looking at the coating straight on or from the side—or, as it turns out, looking at those rough imperfections in the paper—doesn't make much difference to the color. And the paper remains flexible, as usual.

Demonstrating the technique in the cleanroom at the Center for Nanoscale Systems, a National Science Foundation-supported research facility at Harvard, Kats uses a machine called an electron beam evaporator to apply the gold and germanium coating. He seals the paper sample inside the machine's chamber, and a pump sucks out the air until the pressure drops to a staggering 10^{-6} Torr (a billionth of an atmosphere). A stream of electrons strikes a piece of gold held in a carbon crucible, and the metal vaporizes, traveling upward through the vacuum until it hits the paper. Repeating the process, Kats adds the second layer. A little more or a little less germanium makes the difference between indigo and crimson.



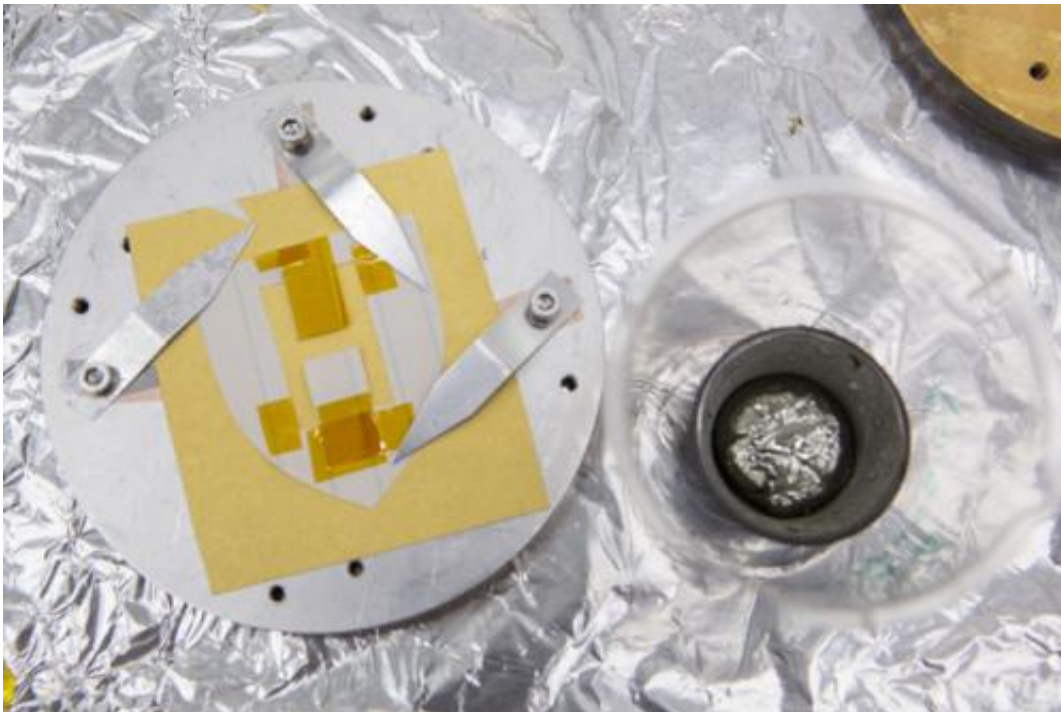
Kats used an electron-beam evaporator in the cleanroom at the Center for Nanoscale Systems to perform thin-film deposition. 'This is one of the most practical, easy-to-use tools,' he says. Credit: Eliza Grinnell

This particular lab technique, Kats points out, is unidirectional, so to the naked eye very subtle differences in the color are visible at different angles, where slightly less of the metal has landed on the sides of the paper's ridges and valleys. "You can imagine decorative applications where you might want something that has a little bit of this pearlescent look, where you look from different angles and see a different shade," he notes. "But if we were to go next door and use a reactive sputterer instead of this e-beam evaporator, we could easily get a coating that conforms to the surface, and you wouldn't see any differences."

Many different pairings of metal are possible, too. "Germanium's cheap. Gold is more expensive, of course, but in practice we're not using much of it," Kats explains. Capasso's team has also demonstrated the technique

using aluminum.

"This is a way of coloring something with a very thin layer of material, so in principle, if it's a metal to begin with, you can just use 10 nanometers to color it, and if it's not, you can deposit a metal that's 30 nm thick and then another 10 nm. That's a lot thinner than a conventional paint coating that might be between a micron and 10 microns thick."



Kats has taken a sheet of paper from his cleanroom notebook, coated it in about 30 nanometers of gold, and pinned a paper stencil on top of it. The silver-colored germanium (pictured at right) is ready for application. Credit: Eliza Grinnell

In those occasional situations where the weight of the paint matters, this could be very significant. Capasso remembers, for example, that the external fuel tank of NASA's space shuttle used to be painted white.

After the first two missions, engineers stopped painting it and saved 600 pounds of weight.

Because the metal coatings absorb a lot of light, reflecting only a narrow set of wavelengths, Capasso suggests that they could also be incorporated into optoelectronic devices like photodetectors and solar cells.

"The fact that these can be deposited on flexible substrates has implications for flexible and maybe even stretchable optoelectronics that could be part of your clothing or could be rolled up or folded," Capasso says.

Harvard's Office of Technology Development continues to pursue commercial opportunities for the new color coating technology and welcomes contact from interested parties.

Kats, who concludes his year-long postdoctoral research position at SEAS this month, will become an assistant professor at the University of Wisconsin, Madison, in January. He credits those many hours spent in Harvard's state-of-the-art laboratory facilities for much of his success in applied physics.

"You learn so much while you're doing it," Kats says. "You can be creative, discover something along the way, apply something new to your research. It's marvelous that we have students and postdocs down here making things."

Provided by Harvard University

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