Plasmonics: Revolutionizing light-based technologies via electron oscillations in metals

June 22 2015, by Hans-Peter Wagner And Masoud Kaveh-Baghbadorani

The beauty of stained glass – all down to electron oscillations. Credit: LoggaWiggler

For centuries, artists mixed silver and gold powder with glass to fabricate colorful windows to decorate buildings. The results were impressive, but they didn't have a scientific reason for how these ingredients together made stained glass. In the early 20th century, the physicist Gustav Mie figured out that the color of a metal nanoparticle is related to its size and the optical properties of the metal and adjacent materials.

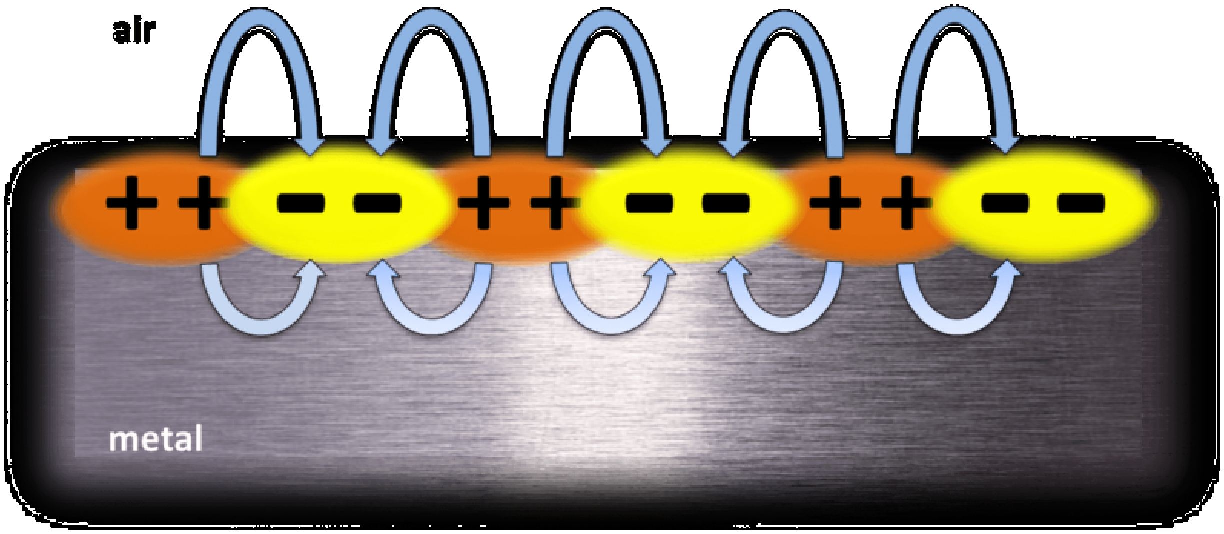
Researchers have only recently figured out the missing piece of this puzzle. Medieval glass workers would be surprised to find out they were harnessing what scientists today call plasmonics: a new field based on electron oscillations called plasmons.

Concentrating light

Plasmonics demonstrates how light can be guided along metal surfaces or within nanometer-thick metal films. It works like this: on an atomic level, metal crystals have a very organized lattice structure. The lattice contains free electrons, not closely associated with the metal atoms, that interact with the light that hits them.

These free electrons collectively start to oscillate with respect to the fixed position of positively charged nuclei in the metal lattice. Like the density of air molecules in a sound wave, the electron density fluctuates in the metal lattice as a plasmon wave.

Visible light, which has a wavelength of approximately half a micrometer, can thus be concentrated by a factor of nearly 100 to travel through metal films just a few nanometers (nm) thick. That's 1,000 times smaller than a human hair. The new mixed light-electron-wave-state empowers intense light-matter interactions with unprecedented optical properties.

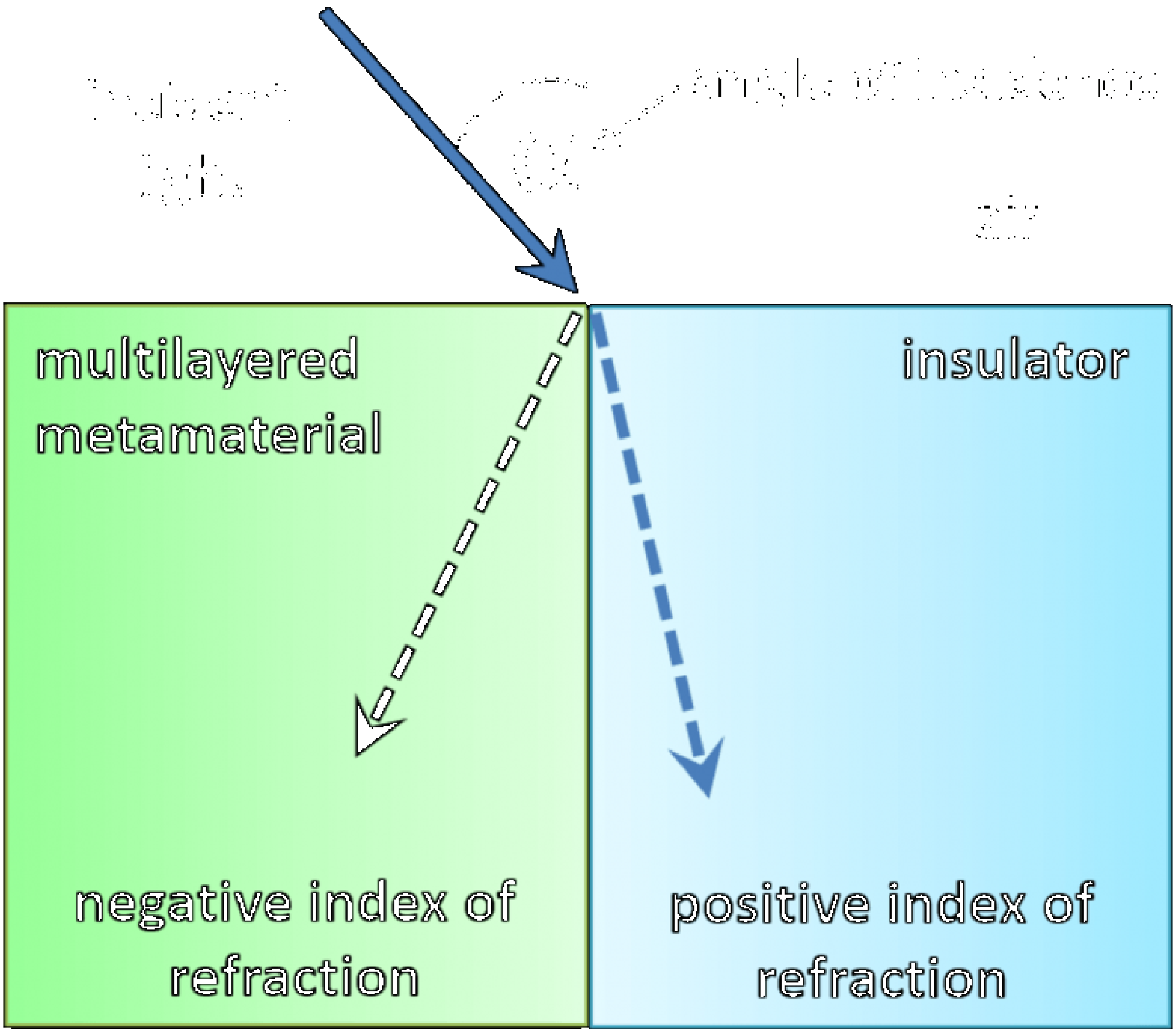


Simplified sketch of electron oscillations (plasmons) at the metal/air interface. Orange and yellow clouds indicate regions with lower and higher electron concentration, respectively. Arrows show electric field lines in and outside of the metal. Credit: Hans-Peter Wagner and Masoud Kaveh-Baghbadorani, CC BY-ND

What can plasmonics do?

Plasmonics could revolutionize the way computers or smartphones transfer data within their electronic integrated circuits. Data transfer in current electronic integrated circuits happens via the flow of electrons in metal wires. In plasmonics, it's due to oscillatory motion about the positive nuclei. Data transfer is therefore more time-consuming in the old technology. Since plasmonic data transfer happens with light-like waves and not with a flow of electrons (electrical current) as in conventional metal wires, the data transmission would be superfast (close to the speed of light) – similar to present glass fiber technologies. But plasmonic metal films are more than 100 times thinner than glass fibers. This could lead to faster, thinner and lighter information technologies.

Surface plasmons also are exceptionally sensitive to any material next to the [metal film](). A low concentration of atoms, molecules or bacteria bound to the metal surface can change the property of its plasmons. This feature can be used for biological and chemical sensing at extremely low concentrations – for instance, to examine polluted water.



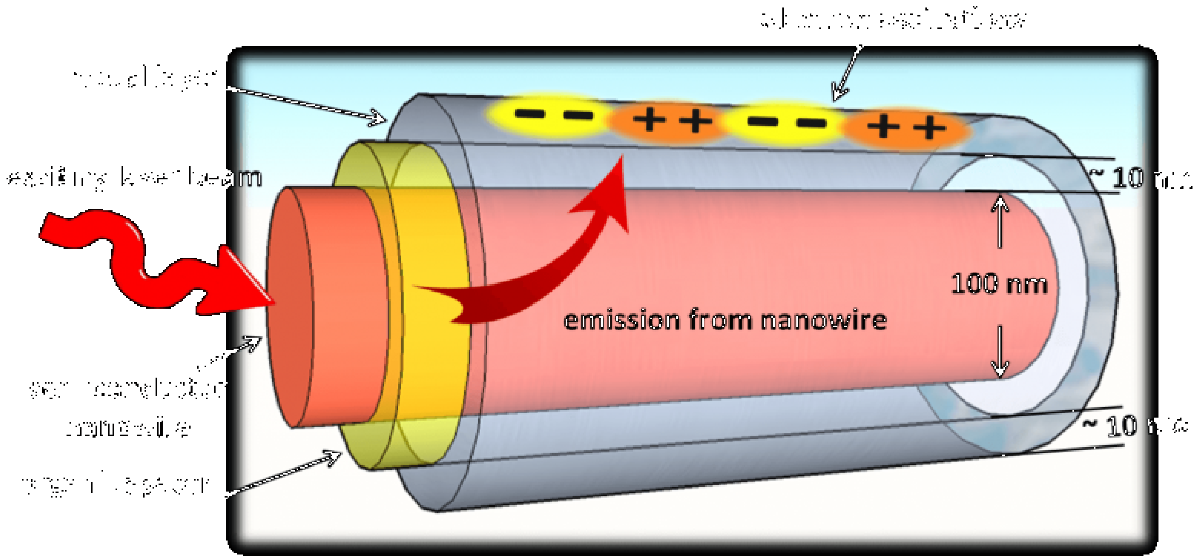
Light changes its direction when it enters a transparent insulator with positive refractive index or a metamaterial with negative refractive index. Credit: Hans-Peter Wagner and Masoud Kaveh-Baghbadorani, CC BY-ND

If properly designed, multilayers of plasmonic metal/insulator nanostructures form artificial metamaterials, where the Greek word "meta" means "beyond." Unlike any other material in nature, these metamaterials have a negative index of refraction. That's a measure of how much light changes its direction when it enters a transparent insulator. Insulators, including glass, have a positive refractive index; they bend light that enters at a certain angle closer to perpendicular to the insulator surface.

In contrast, multilayered metamaterials bend light to the "opposite" direction. This fascinating property can be used to cloak objects by covering them with a metamaterial wrap. The foil guides the light smoothly around the object instead of reflecting it. Almost unbelievably, the cloaked object becomes invisible.

Other applications include optical superlenses with significantly higher resolution compared to regular optical microscopes. They could allow scientists to see objects as small as about 100 nm in size. That's about one-tenth as big as a typical germ.

A few proof-of-principle optical cloaks and superlenses do exist. But high resistivity losses in the metal layers which convert the light-electron-wave energy into heat currently limit the feasibility of many applications.

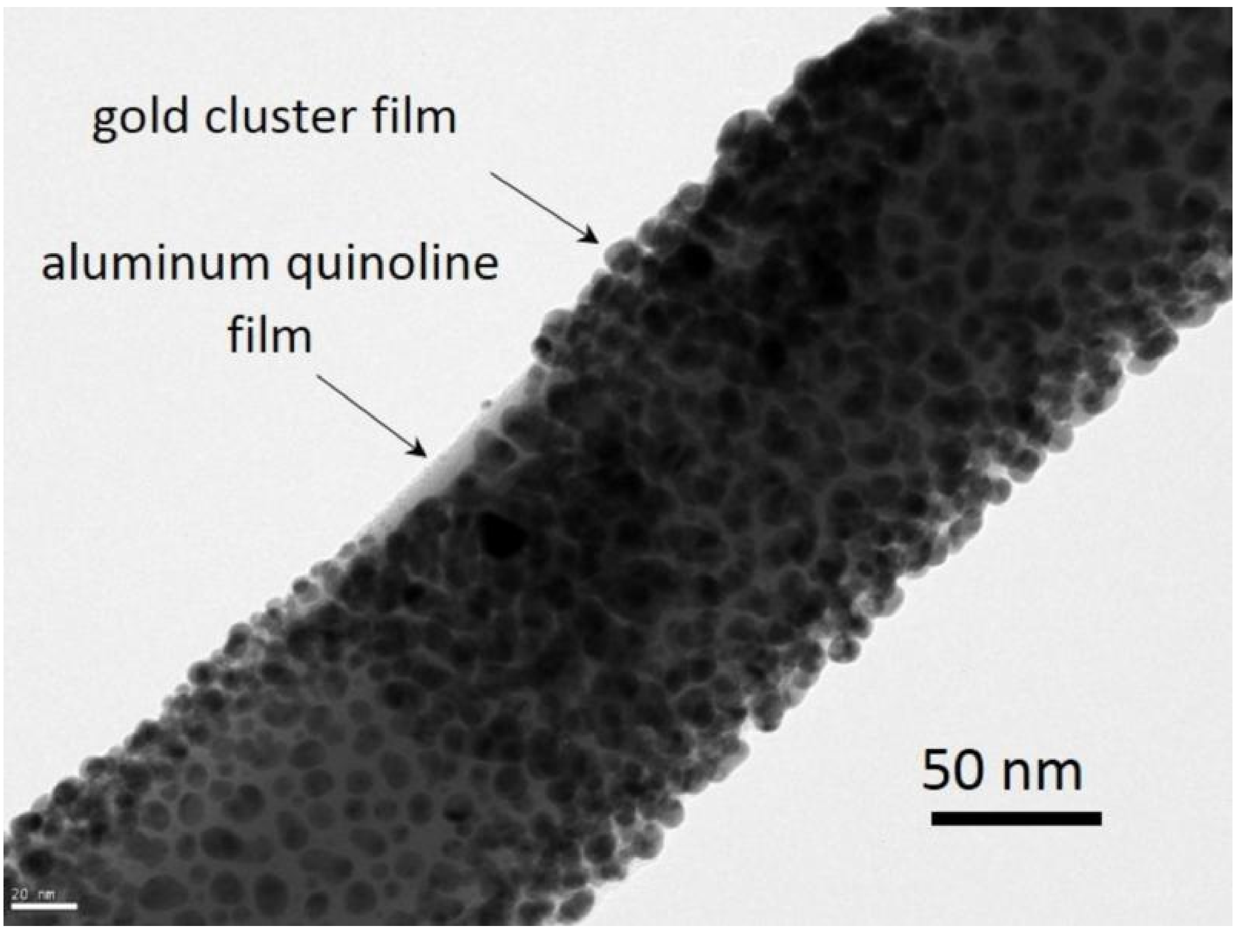


Simplified sketch of a plasmonic metal/organic/semiconductor nanowire heterostructure. The emission from the nanowire generated by the exciting laser beam is used as an energy pump to compensate for resistivity losses in the metal shell. An organic spacer layer of few 10 nm thickness is inserted to control this energy transfer. Credit: Hans-Peter Wagner and Masoud Kaveh-Baghbadorani, CC BY-NC-ND

Manufacturing plasmonic nanowires

High resistivity losses are the major issue with plasmonics. To overcome these limitations, we design and fabricate unique plasmonic metal/organic/semiconductor nanowire heterostructures. Our goal is to excite the semiconductor nanowires with an external light source, then use the internal radiation in the nanowires as an energy-pump source to compensate for metallic losses. This way, the nanowires couple light energy in concert with the light-electron-oscillations to the metal film, thus restoring the amplitude of the damped plasmon wave.

We use the organic molecular beam deposition (OMBD) method to coat the semiconductor nanowires with metal/organic multilayers. In the OMBD chamber, organic and metal materials reside in heatable cylindrical cells. We evaporate both organic molecules and metal atoms in heated cells at ultra-high vacuum (which is hundreds of billion times lower than atmosphere pressure). Then we direct the molecular and atom beams we have produced toward the semiconductor nanowire sample. The thickness of the resulting deposited film on the nanowire is controlled by mechanical shutters at the cell openings.



Transmission electron microscope (HRTEM) image of a GaAs-AlGaAs core-shell nanowire coated with nominally 10 nm aluminum quinoline and a 5 to 10 nm thick gold cluster film on top. Credit: Melodie Fickenscher (Advanced Materials Characterization Center College of Engineering and Applied Science)

The energy-transfer processes from the optically excited semiconductor nanowire to the plasmon oscillations in the surrounding metal film are studied with ultrafast spectroscopic techniques.

Results from our studies will provide a new understanding of light-electron-waves in the novel and unique metal-semiconductor environment. Hopefully, we will open new prospects for designing low-loss or loss-free plasmonic devices. Ideally we want to enable new and important applications in information technologies, biological sensing and national defense. We further envision our investigations having a strong impact in other research fields: for instance, by utilizing the biocompatibility of our hybrid organic/metal structures, by enhancing the light emission in light-emitting diodes and laser structures or by improving light harvesting in photovoltaic devices.

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