VIEW FROM... NANOMETA 2011

In search of new materials

Metals are widely used throughout the fields of plasmonics and metamaterials owing to their unique focusing capabilities. Research has now shown that doped, low-loss semiconductors compatible with standard nanoelectronic fabrication processes could outperform metals in certain applications.

Rachel Won

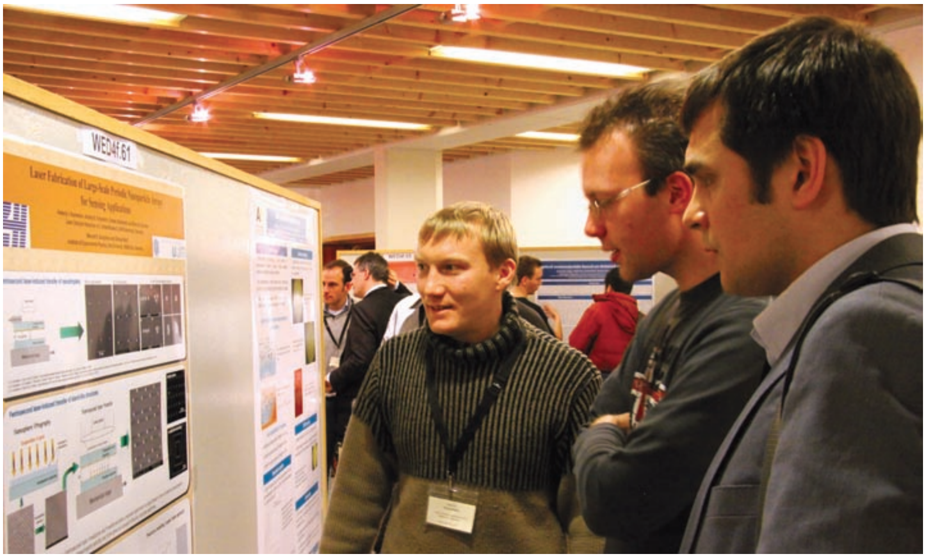
Metals such as silver and gold have traditionally been the materials of choice in the fields of metamaterials and plasmonics. However, recent research suggests that doped, low-loss semiconductors could be an excellent alternative. This was the message at the recent 3rd International Topical Meeting on Nanophotonics and Metamaterials (NANOMETA 2011), held on 3–6 January 2011 in Seefeld, Austria.

Metallic nanostructures are well-known for their unrivalled ability to concentrate light to subwavelength volumes using collective electron excitations known as surface plasmons. However, as the fields of metamaterials and plasmonics progress towards exploiting the different sizes, shapes and positions of metallic nanostructures for more advanced applications, it has become apparent that high optical losses resulting from light-induced resistive heating in metals can be detrimental to the performance of many plasmonic and metamaterial applications at near-infrared and visible wavelengths. Reducing losses in metals or searching for ever-elusive lossless metals are truly daunting challenges.

“Compensating losses with optical gain is one possible solution,” said Mark Brongersma from Stanford University in the USA. Recent work in this area includes the use of optically active dielectric core materials and the incorporation of gain material into the high-local-field areas of metamaterials. However, Brongersma explained that these approaches may not be feasible for chip-scale photonic applications in which energy dissipation is a key problem; introducing gain does not always help with the dissipation of heat, and the additional losses in the gain material will further increase local heating.

Another vital parameter for determining the performance of a system is the real part of a material’s permittivity.

“The large negative real permittivities of metals make them unsuitable for metamaterial devices such as hyperlenses, which often require the opposing polarization responses of their plasmonic and dielectric components to be balanced,” said Alexandra Boltasseva from Purdue University in the USA and the Technical University of Denmark. Creating a metamaterial with an effective permittivity close to zero therefore requires the real permittivity of the material’s dielectric component to match that of its plasmonic component, explained Boltasseva.



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Participants exchanging ideas during the interactive poster session.

It is clear that both low loss and tunability over the real part of the permittivity are the two requirements of new materials.

“Low-loss semiconductors could be used as plasmonic materials through appropriate doping to achieve small negative real permittivities at infrared and longer wavelengths,” said Boltasseva.

Doping in this case involves making a semiconductor ‘more metallic’ through the addition of metal impurities, thereby allowing its optical properties to be tuned. In addition, the compatibility of semiconductors with standard nanoelectronic fabrication processes provides an additional advantage for their use as building blocks for advanced optical technologies, particularly in the realm of photonic integrated circuits, optical communications and computing.

According to Boltasseva, qualifying as a low-loss plasmonic material requires both the bandgap and the plasma frequency of the semiconductor to be larger than the frequency range of interest. To achieve small negative real permittivities in semiconductors, a large carrier concentration in the range of ~10^{21} cm^{-3} is needed.

At the conference, Boltasseva presented her recent findings on transparent conducting oxides such as zinc oxide doped with aluminium or gallium, which were found to have real negative permittivities in the near-infrared region and losses four times lower than those of silver. She compared the use of metals and highly doped low-loss semiconductors in waveguides, superlenses and hyperlenses, and explained that although semiconductor waveguides provide better confinement than gold or silver waveguides, they do so at the cost of reduced propagation length. The figure of merit for semiconductor single-slab superlenses in the near-infrared region is around 0.3, which is slightly better than for metals. Using semiconductors for hyperbolic metamaterials and hyperlenses boosts the figure of merit to 60, which is extremely large when compared with the near-zero value for metals in the near- and mid-infrared regions.

“Metals suffer from high interband transition losses in the near-infrared, where there are important telecommunications frequencies. Transparent conducting oxides have dielectric constants that are tunable through doping, which makes them interesting alternatives to metals," commented Brongersma.

Another recent development was a hyperbolic metamaterial multilayered stack of zinc oxide and aluminium-doped zinc oxide, which was shown to be a good candidate for developing quantum optics devices in the near-infrared region by engineering the photonic density of states.

Semiconductors also exhibit useful plasmonic and phonon–polaritonic effects for realizing interesting thermal and metamaterial devices in the mid-infrared region, with silicon carbide showing particular potential.

"Silicon carbide can support a different type of surface wave — a surface phonon–polariton — at frequencies near the transverse optical phonon resonance," explained Brongersma, who recently achieved control over the thermal radiation from individual silicon carbide subwavelength infrared resonant antennas and also suggested new types of metamaterials based on electric and magnetic Mie resonances of silicon carbide particles.

"It can be anticipated that semiconductors and intermetallics will replace metals as low-loss, tunable CMOS-compatible materials that could enable full-scale development of plasmonic and metamaterial devices," said Boltasseva.

For Brongersma, the most exciting option may be to integrate metallic and semiconductor nanostructures into new devices that capitalize on the best properties of metals (light concentration and high electrical conductivity) and semiconductors (light emission and photocurrent generation).

"I envision new types of photodetectors, modulators and optical sources benefitting from low-loss plasmonic structures that can perform simultaneous electronic and optical functions," said Brongersma.

It will be interesting to see whether semiconductors will prevail as a promising material for next-generation plasmonic and metamaterial devices or whether they will be reserved for very limited applications.

Comprising around 280 oral and poster presentations, NANOMETA 2011 brought together over 250 attendees from 30 countries to present recent research progresses and share upcoming research directions in transformation optics, metamaterials, plasmonics, near-field optics, optical super-resolution and nanobiophotonics. ❐

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Correction

In the Research Highlights for the February issue (*Nature Photon.* **5,** 68–69; 2011), the image for 'Stable and tunable' should have been for 'In the frequency domain'.

In the News & Views 'Optical black-hole analogues' (*Nature Photon.* **5,** 76–78; 2011), the name of physicist Francesco Belgiorno was misspelt as 'Franco'.

Both errors have been corrected in the HTML and PDF versions.