

In their article recently published online in *Nature Photonics* (DOI: 10.1038/NPHOTON.2012.2), Tassin and co-researchers consider metamaterials as an array of subwavelength conducting elements, which effectively captures the physics of the most commonly studied systems. The researchers derived an expression for the dissipated power fraction as a function of four independent parameters. However, only two parameters depend on the material's properties—the dissipation factor,  $\zeta$ , and the kinetic inductance factor,  $\xi$ , which are proportional to the real and imaginary parts of the resistivity, respectively. A small  $\zeta$  allows for large currents, while a small  $\xi$  prevents saturation of the resonance frequency. Furthermore, at frequencies where the permeability is  $-1$ , the dissipative loss depends, to a good approximation, only on  $\zeta$ . This establishes it as a good figure of merit for

conducting materials in resonant metamaterials, although geometrical factors are important when comparing samples of different thicknesses.

The researchers said that although charge-neutral graphene displays minimal resistivity in the mid-infrared and visible band, it is not a good candidate for metamaterial applications because  $\zeta$  and  $\xi$  for graphene are several orders of magnitude larger than those for gold. Similarly, silver performs better as a conducting material at terahertz frequencies than high- $T_c$  superconductors because it has significantly smaller  $\zeta$  and  $\xi$  values. Transparent conducting metal oxides, such as indium tin oxide and aluminum tin oxide, have also recently been proposed for use in metamaterials, but the researchers found that their microwave resistivities are two orders of magnitude larger than the optical resistivity of silver.

For plasmonics, the researchers use

the ratio of the propagation length to the surface plasmon wavelength as the measure of loss performance. The larger kinetic inductance of biased graphene makes it a better candidate for plasmonic applications than charge-neutral graphene. However, the researchers also showed that the propagation length is, at best, on the order of a few SPP wavelengths, which is too short for most plasmonic applications.

The researchers also discussed why alkali-noble intermetallics, such as KAu and LiAg, are not good candidates for use in metamaterials, although they said, "These examples show, nevertheless, the possibility of band engineering to tune the resistivity of alloys," and that, "it is worth continuing the research effort to develop better conducting materials, because of the considerable improvement such materials would bring."

**Steven Trohalaki**

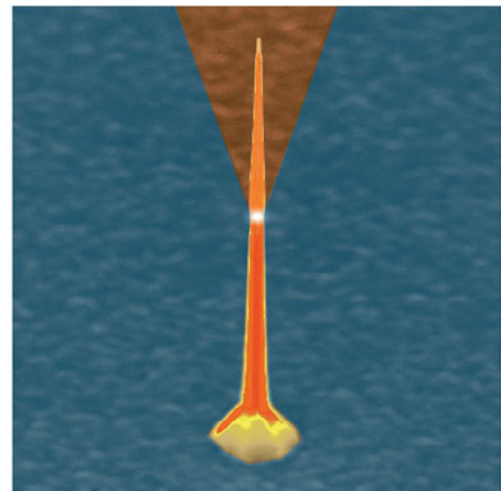
### Nano Focus

#### Tailored nanowire with embedded quantum dot yields bright single-photon source

Single-photon sources with near-unity light-extraction efficiencies ( $\eta$ ) are ideally required for processes relying on the transfer of quantum information between two remote stationary quantum bits, such as quantum cryptography or the development of a quantum computer. Moving toward this goal, M.E. Reimer and co-workers, from the Delft University of Technology and M.A. Verheijen and E.P.A.M. Bakkers from the Eindhoven University of Technology, The Netherlands, have recently succeeded in developing a highly efficient method of collecting single photons. As reported in the March 13 issue of *Nature Communications* (DOI: 10.1038/ncomms1746), the researchers have fabricated a high-efficiency single-photon source based on a nanowire with controlled shape, which they suggest will pave the way toward a single-photon source with near-unity light-collection efficiency.

The researchers designed a tapered

nanowire as a waveguide where a single  $\text{InAs}_{0.25}\text{P}_{0.75}$  quantum dot was precisely positioned on its axis such that it can collect photons as they are generated. This was achieved by growing InP nanowires using low pressure metal-organic vapor-phase epitaxy (MOVPE) methods, and then synthesizing the  $\text{InAs}_{0.25}\text{P}_{0.75}$  quantum dot at a specific time such that it was incorporated at approximately half the nanowire length. Finally, the temperature was raised to suppress axial growth and favor shell formation, which allowed the nanowire geometry to be shaped to an optimum nanowire diameter of 160–220 nm at the quantum dot position, with a tapering angle toward the tip ( $\sim 2^\circ$ ) (see Figure). This design overcomes the principal drawback of existing devices where quantum dots are randomly positioned in the nanowire, leading to a drastic reduction in the collection efficiency. Furthermore, with



A stream of single photons is directed toward the tapered nanowire waveguide tip with high efficiency (42%). The single quantum dot positioned in the middle of the nanowire couples to the fundamental waveguide mode with efficiencies exceeding 95%, such that the photons are emitted along the nanowire axis. The nanowire diameter is approximately 200 nm.

this very small nanowire taper the researchers also avoided unwanted reflections at the semiconductor-air interface.

A final important feature of this novel nanostructure design was the integration



of a bottom mirror to reflect downward emitted photons back to the nanowire tip. The researchers integrated a gold mirror at the nanowire base by transferring the

nanowires into a flexible and fully transparent polymer film and coating it with the metal by evaporation. Through this novel approach the researchers were able

to achieve a 20-fold enhanced single-photon emission flux.

Joan J. Carvajal

### Nano Focus

**Nanoporous carbon electrode supercapacitors store more charge by efficiently adsorbing electrolyte ions**

The recent discovery that microporous carbide-derived carbon electrodes have higher capacitances than their mesoporous counterparts, and thus that they can act as supercapacitors able to store high amounts of electrical energy, has inspired an international team of researchers to investigate the origin of this phenomenon. Together with their collaborators in France, the United Kingdom, and the United States, C. Merlet, B. Rotenberg, and M. Salanne from the Université Pierre et Marie Curie in Paris sought to answer whether the increased capacitance derives from the additional surface area in the micropores, or whether the pore structure also contributes to this effect. Their findings are published in the April issue of *Nature Materials* (DOI: 10.1038/NMAT3260; p. 306).

The researchers used molecular dynamics (MD) simulations of microporous carbon and a 1-butyl-3-methylimidazolium hexafluorophosphate (BMI-PF<sub>6</sub>) ionic liquid to develop a picture of an ionic liquid adsorbed in microporous carbon. Merlet's MD study found that the ion coordination in nanoporous electrodes was significantly different from the layered arrangement which had previously been accepted, and that the number of BMI<sup>+</sup> cations coordinated around a PF<sub>6</sub><sup>-</sup> anion was reduced inside the electrode as compared with the bulk liquid, and decreased further again on application of a positive potential to the electrode. An analogous result occurred

for the opposite coordination under applied negative potentials (see Figure). Commenting on their findings the researchers said, "The volume occupied by the liquid in the [nanoporous] electrode remains almost constant, but the ratio of numbers of ions of different charges deviates substantially from unity. . . . The charging mechanism involves the exchange of ions between the electrodes and the bulk electrolyte, and not the filling of the pores by the liquid."

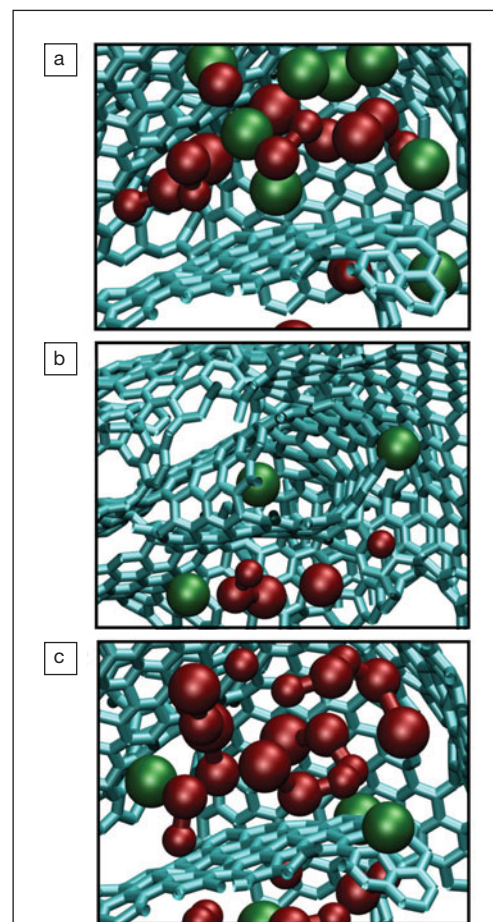
Building on this insight, comparison of simulations of nanoporous carbon with those of planar graphite revealed that the ions in the porous electrode were on average located closer to the accessible surfaces than in graphite. As capacitance is inversely proportional to the distance between opposite charges, the shorter distance would result in increased capacitance. The researchers also found that far fewer ions adsorbed onto the surface in nanoporous carbon, but that the surface of the electrode exactly balanced the charge of those adsorbed ions. The charge storage in the nanoporous electrode was therefore much more efficient, where the pores enhanced the capacitance by confining ions and preventing overscreening.

According to the researchers, further developments in electrical energy storage may also be possible, where control over pore geometries and ion size may enable the capacitance to be tailored.

Co-authors on the article are P.A. Madden of the University of Oxford; P.-L. Taberna of RS2E and Université Paul Sabatier; P. Simon of RS2E, Saba-

tier, and Institut Universitaire de France; and Y. Gogotsi of Drexel University.

Ashley Predith



The figure shows typical structures of BMI-PF<sub>6</sub> ionic liquid inside a realistic, nanoporous carbide-derived carbon in a molecular dynamics simulation (C-C bonds in blue, BMI<sup>+</sup> cations in red, and PF<sub>6</sub><sup>-</sup> anions in green) where (a) depicts the enhanced anion density at a +0.5 V positively polarized surface, (b) shows a PF<sub>6</sub><sup>-</sup> anion in a +0.5V polarized cylindrical pore, and (c) shows enhanced BMI<sup>+</sup> cation density at a -0.5V negatively polarized surface. Reproduced with permission from *Nature Materials* **11** (2012), DOI: 10.1038/NMAT3260; p. 306. ©2012 Macmillan Publishers Ltd.

### Correction

In the March 2012 issue of *MRS Bulletin*, the following reference was omitted from the Rondinelli et al. article: E. Bousquet, M. Dawber, N. Stucki, C. Lichtensteiger, P. Hermet, S. Gariglio, J.M. Triscone, P. Ghosez, *Nature* **452**, 732 (2008). This should have been cited in place of Reference 47 on pages 263 (second citation), 268, and 269.