Nano Focus

Scanning thermoelectric microscopy locates extra electrons outside quantum dots

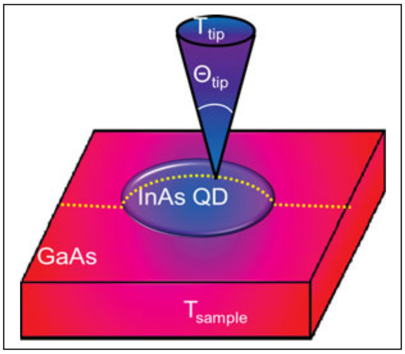
Semiconducting quantum dots (QDs) can be used to enhance the performance of a variety of devices encompassing optoelectronic, thermoelectric, and alternative energy technologies. Often, a small amount of another element must be added to the semiconducting QDs to provide extra electrons and improve conductivity. At the nanoscale, these extra electrons are difficult to locate. Rachel Goldman and her colleagues at the University of Michigan have now shown the feasibility of such measurements.

As reported in the May 11 issue of *Applied Physics Letters* (DOI: 10.1063/1.4919919; 192101), the researchers used scanning thermoelectric microscopy to locate electrons in semiconducting QDs on surfaces. Beginning with high-purity solid Ga, As_2, and In as the raw materials, they used molecular beam epitaxy and employed Stranski–Krastanov growth to fabricate InAs QDs on a GaAs substrate. Such structures can be doped with another element, such as Si, to provide extra electrons. However, it is difficult to predict how many of the dopants will incorporate into a QD rather than into the surrounding layers. Each QD is believed to contain fewer than 10 dopant atoms, making them particularly challenging to locate.

The researchers then used a scanning thermoelectric microscope (SThEM) with a specially prepared tungsten tip. The measurements were performed in ultrahigh vacuum, and the sample was heated a few Kelvins above room temperature for several hours to achieve a uniform temperature in the QD, surrounding layers, and substrate. Upon contact, the SThEM tip locally cools the QD, causing the extra electrons in the hot sample to travel toward the cold tip, generating a thermoelectric voltage. Since this voltage depends on the number of electrons, the research team was able to locate those extra electrons using measurements at several points across the QD.

Specifically, the dependence of the thermoelectric voltage on the thermopower allowed the researchers to locate the extra electrons: they found fewer electrons within the interior of the QD than in the surrounding substrate, which could mean that the silicon "dopants" prefer to stay outside the QD.

"We were really interested in measuring the thermopower, since QDs are considered promising for thermoelectrics," doctoral student and NSF Fellow Jenna Walrath wrote of her original goals for the research. Goldman and Walrath were surprised by the unusual behavior of the QD thermopower, and their efforts to explain it led them to locating the extra electrons.



Schematic of the scanning thermoelectric microscope setup, which consists of a room-temperature probe tip in contact with a heated sample. The yellow dashed line represents the measurement points of the thermoelectric voltage at each tip-sample contact. Reproduced with permission from *Appl. Phys. Lett.* **106**, 192101 (2015); DOI: 10.1063/1.4919919.

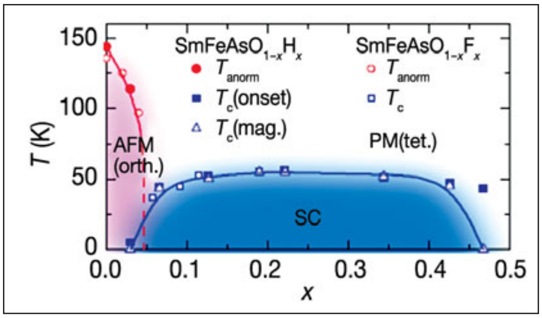
"While the answer wasn't that exciting for thermoelectrics, understanding how dopants incorporate into nanostructures is unprecedented. The lessons learned from this work provide a pathway toward strategic placement of just a few dopants at a time," Walrath says.

Their work could be extended to other nanostructures such as quantum wells and nanowires. "The potential of SThEM is just beginning to be explored," Goldman says, "so I expect it will continue to play a central role in bridging atoms to devices."

Antonio Cruz

In pursuit of novel superconductors: Four years and ~1000 materials

Over 100 previously unknown superconducting materials ranging from new iron-based superconductors (IBSCs or pnictide semiconductors) to titanium- and cobalt-based ones are listed in a review article by Hideo Hosono and colleagues, published in the June issue of *Science and Technology of Advanced Materials* (DOI: 10.1088/1468-6996/16/3/033503). The article summarizes the results of a four-year long research project funded as part of FIRST (Funding Program for World-Leading Innovative R&D on Science and Technology), a Japanese government-funded program. Six Japanese research groups collaborated under the leadership of Hosono from the Tokyo Institute of Technology to pursue multiple goals in the field of superconducting materials, the fabrication of prototype devices based on superconducting wires and tapes, and exploration of new functionality of relevant materials. The article encompasses detailed discussions on crystal structure investigations. The electronic structure and phase diagrams are shown



Electronic phase diagram of $SmFeAsO_{1-x}H_x$ superimposed over that of $SmFeAsO_{1-x}F_x$. Reprinted with permission from *Phys. Rev. B* **84**, 024521. © 2011 American Physical Society.

https://doi.org/10.1557/mrs.2015.204 Published online by Cambridge University Press

for many of the materials discovered from 2010 to 2014 as part of the FIRST project.

Among other goals, the researchers had proposed to discover a new iron-based superconductor with a critical temperature (T_c) >77 K. The researchers did not meet this particular self-set goal, but one research highlight of the study is the observation that hydride ions (H^-) can be used as an electron dopant in place of fluoride (F^-) to induce superconductivity in IBSC materials. This approach yields, for example, $SmFeAsO_{1-x}H_x$ with a critical temperature T_c of 56 K, the superconducting material with the highest T_c reported in the review article (see Figure).

IBSCs exhibit a layered crystal structure. Taking this into consideration, a significant portion of the review article describes the syntheses and properties of various superconducting intercalation compounds, not limited to IBSCs. The section is followed by studies on changes in critical current density based on microstructural grain variations in tape connectors, with the article culminating in describing devices such as the first bipolar oxide thin-film transistors that can be applied to complementary metal–oxide–semiconductor circuits and a new catalyst based on an electride superconductor (heavily electron-doped $12CaO{\cdot}7Al_2O_3$) for ammonia synthesis at ambient pressure.

It is noteworthy that the researchers not only report the new superconductor materials they found, but they also list ~700 materials they either unsuccessfully attempted to synthesize or that did not exhibit the desired superconductivity. Presentation of tables of null results like these are a return to the early days of intermetallic superconductivity, when it was common practice to present summaries of measurements on failed superconductors as well as successful ones. "These tables are very useful," says Paul C. Canfield, Distinguished Professor of Physics at Iowa State University, a Senior Physicist at Ames Laboratory, and a long-time researcher in the field of superconductivity, who was not involved in the study. "They help researchers focus their searches for new materials. Across the globe there are efforts to find new superconducting compounds, but the scope of these efforts is miniscule compared to the number of known, as well as unknown, compounds. We are all exploring a wilderness of phase space, and any signs left on the trail by earlier researchers are valuable."

Birgit Schwenzer

https://doi.org/10.1557/mrs.2015.204 Published online by Cambridge University Press