Engineers develop first transistors made entirely of nanocrystal 'inks'

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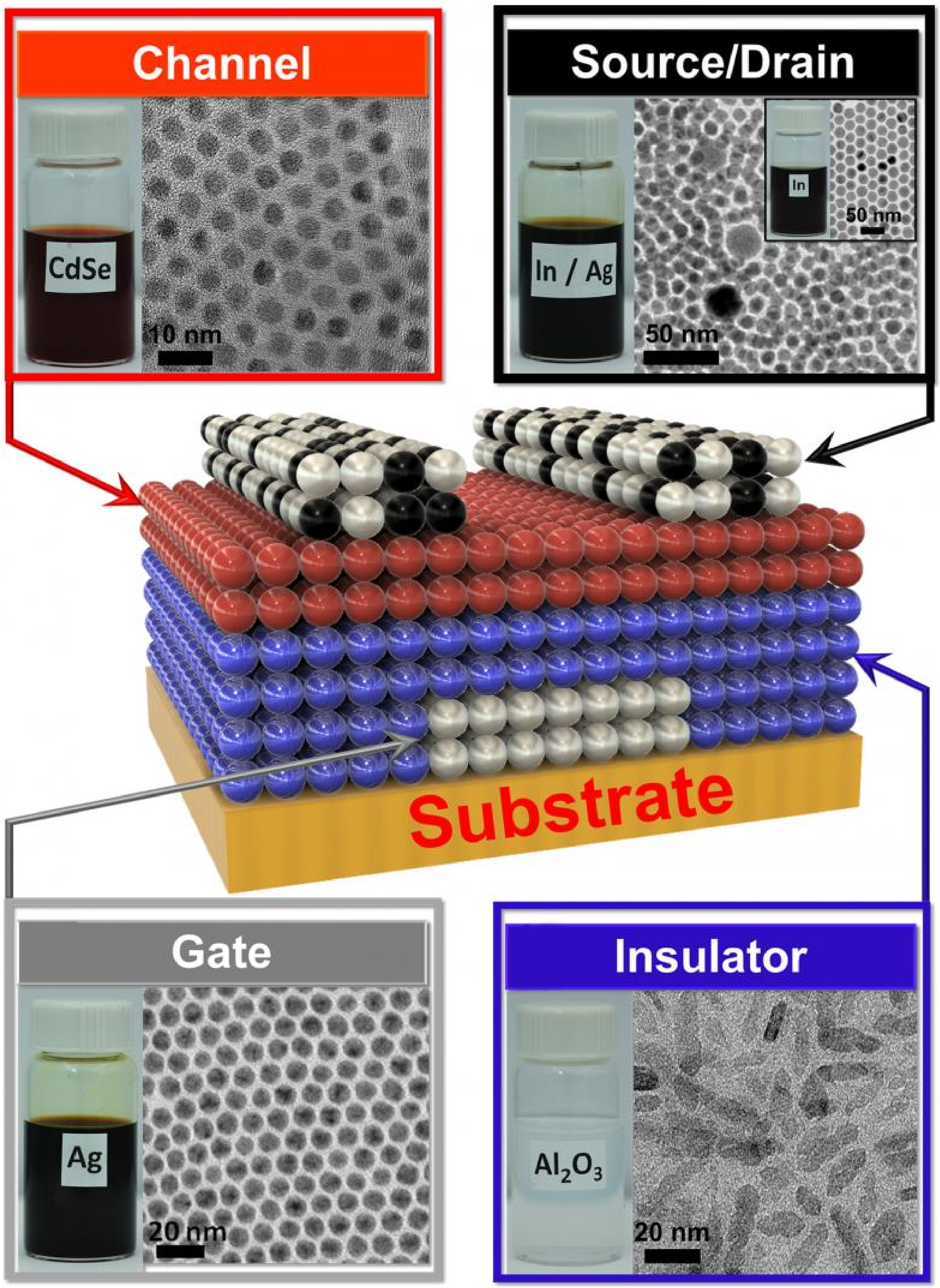


Channel
CdSe
10 nm
Source/Drain
In / Ag
In
50 nm
50 nm
Substrate
Gate
Ag
20 nm
Insulator
Al_2O_3
20 nm

Kagan's group developed a library of four nanocrystal inks that comprise the transistor: a conductor (silver), an insulator (aluminum oxide), a semiconductor (cadmium selenide) and a conductor combined with a dopant (a mixture of silver and indium). Doping the semiconductor layer of the transistor with impurities controls whether the device transmits a positive or negative charge. Credit: University of Pennsylvania

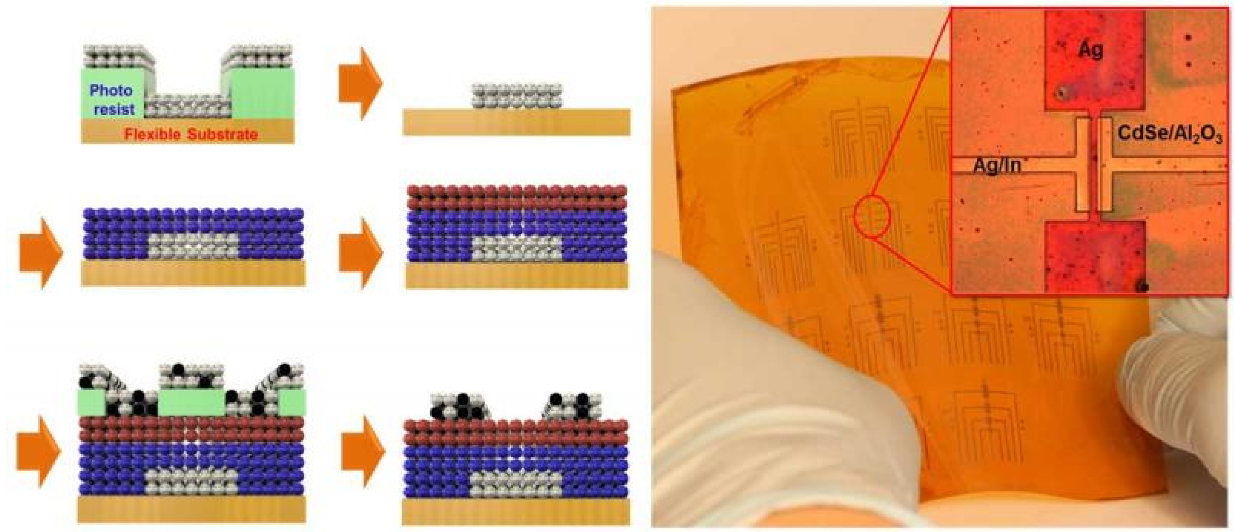
The transistor is the most fundamental building block of electronics, used to build circuits capable of amplifying electrical signals or switching them between the 0s and 1s at the heart of digital computation. Transistor fabrication is a highly complex process, however, requiring high-temperature, high-vacuum equipment.

Now, University of Pennsylvania engineers have shown a new approach for making these devices: sequentially depositing their components in the form of liquid nanocrystal "inks."

Their new study, published in *Science*, opens the door for electrical components to be built into flexible or wearable applications, as the lower-temperature process is compatible with a wide array of materials and can be applied to larger areas.

The researchers' nanocrystal-based field effect transistors were patterned onto flexible plastic backings using spin coating but could eventually be constructed by additive manufacturing systems, like 3-D printers.

The study was lead by Cherie Kagan, the Stephen J. Angello Professor in the School of Engineering and Applied Science, and Ji-Hyuk Choi, then a member of her lab, now a senior researcher at the Korea Institute of Geoscience and Mineral Resources. Han Wang, Soong Ju Oh, Taejong Paik and Pil Sung Jo of the Kagan lab contributed to the work. They collaborated with Christopher Murray, a Penn Integrates Knowledge Professor with appointments in the School of Arts & Sciences and Penn Engineering; Murray lab members Xingchen Ye and Benjamin Diroll; and Jinwoo Sung of Korea's Yonsei University.



Because this entirely ink-based fabrication process works at lower temperatures than existing vacuum-based methods, the researchers were able to make several transistors on the same flexible plastic backing at the same time. Credit: University of Pennsylvania

The researchers began by taking nanocrystals, or roughly spherical nanoscale particles, with the electrical qualities necessary for a transistor and dispersing these particles in a liquid, making nanocrystal inks.

Kagan's group developed a library of four of these inks: a conductor (silver), an insulator (aluminum oxide), a semiconductor (cadmium selenide) and a conductor combined with a dopant (a mixture of silver and indium). "Doping" the semiconductor layer of the transistor with impurities controls whether the device transmits a positive or negative charge.

"These materials are colloids just like the ink in your inkjet printer," Kagan said, "but you can get all the characteristics that you want and expect from the analogous bulk materials, such as whether they're conductors, semiconductors or insulators.

"Our question was whether you could lay them down on a surface in such a way that they work together to form functional transistors."

The electrical properties of several of these nanocrystal inks had been independently verified, but they had never been combined into full devices.

"This is the first work," Choi said, "showing that all the components, the metallic, insulating, and semiconducting layers of the transistors, and even the doping of the semiconductor could be made from nanocrystals."

Such a process entails layering or mixing them in precise patterns.

First, the conductive silver nanocrystal ink was deposited from liquid on a flexible plastic surface that was treated with a photolithographic mask, then rapidly spun to draw it out in an even layer. The mask was then removed to leave the silver ink in the shape of the transistor's gate electrode. The researchers followed that layer by spin-coating a layer of the aluminum oxide nanocrystal-based insulator, then a layer of the cadmium selenide nanocrystal-based semiconductor and finally another masked layer for the indium/silver mixture, which forms the transistor's source and drain electrodes. Upon heating at relatively low temperatures, the indium dopant diffused from those electrodes into the semiconductor component.

"The trick with working with solution-based materials is making sure that, when you add the second layer, it doesn't wash off the first, and so on," Kagan said. "We had to treat the surfaces of the nanocrystals, both when they're first in solution and after they're deposited, to make sure they have the right electrical properties and that they stick together in the configuration we want."

Because this entirely ink-based fabrication process works at lower temperatures than existing vacuum-based methods, the researchers were able to make several transistors on the same flexible plastic backing at the same time.

"Making transistors over larger areas and at lower temperatures have been goals for an emerging class of technologies, when people think of the Internet of things, large area flexible electronics and wearable devices," Kagan said. "We haven't developed all of the necessary aspects so they could be printed yet, but because these materials are all solution-based, it demonstrates the promise of this materials class and sets the stage for additive manufacturing."

More information: "Exploiting the colloidal nanocrystal library to construct electronic devices" [DOI: 10.1126/science.aad0371](https://doi.org/10.1126/science.aad0371)

Provided by University of Pennsylvania