

# Discovery of 'doping' mechanism in semiconductor nanocrystals

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Novel electronic devices based upon nanotechnology may soon be realized due to a new understanding of how impurities, or 'dopants,' can be intentionally incorporated into semiconductor nanocrystals. This understanding, announced today by researchers at the Naval Research Laboratory (NRL) and the University of Minnesota (UMN), should help enable a variety of new technologies ranging from high-efficiency solar-cells and lasers to futuristic 'spintronic' and ultra-sensitive biodetection devices. The complete findings of the study are published in the July 7, 2005, issue of the journal *Nature*.

Nanocrystals are tiny semiconductor particles just a few millionths of a millimeter across. Due to their small size, they exhibit unique electronic, optical, and magnetic properties that can be utilized in a variety of technologies. To move toward this end, chemical methods have been optimized over the last 20 years to synthesize extremely pure nanocrystals. More problematic, however, has been the goal of controllably incorporating selected impurities into these particles. Conventional semiconductor devices, such as the transistor, would not operate without such impurities. Moreover, theory predicts that dopants should have even greater impact on semiconductor nanocrystals. Thus, doping is a critical step for tailoring their properties for specific applications.

A long-standing mystery has been why impurities could not be incorporated into some types of semiconductor nanocrystals. The findings by NRL and UMN researchers establish the underlying reasons

for these difficulties, and provide a rational foundation for resolving them in a wide variety of nanocrystal systems. "The key lies in the nanocrystal's surface," said Dr. Steven Erwin, a physicist at NRL and lead theorist on the project. "If an impurity atom can stick, or 'adsorb,' to the surface strongly enough, it can eventually be incorporated into the nanocrystal as it grows. If the impurity binds to the nanocrystal surface too weakly, or if the strongly binding surfaces are only a small fraction of the total, then doping will be difficult." From calculations based on this central idea, the team could predict conditions favorable for doping. Experiments at UMN then confirmed these predictions, including the incorporation of impurities into nanocrystals that were previously believed to be undopable. Thus, a variety of new doped nanocrystals may now be possible, an important advance toward future nanotechnologies.

According to Dr. David Norris, an Associate Professor of Chemical Engineering and Materials Science at UMN and the lead experimentalist on the team, "an exciting aspect of these results is that they overturn a common belief that nanocrystals are intrinsically difficult to dope because they somehow 'self-purify' by expelling impurities from their interior. According to this view, the same mechanisms that made it possible to grow very pure nanocrystals also made it extremely difficult to dope them. We have shown that doping difficulties are not intrinsic, and indeed are amenable to systematic optimization using straightforward methods from physical chemistry."

Future efforts will focus on incorporating impurities which are chosen for specific applications. For example, solar cells and lasers could benefit from impurities that add an additional electrical charge to the nanocrystal. In addition, impurities will be chosen to explore the use of nanocrystals in spin electronics (or "spintronics"). Spintronic devices utilize the fact that electrons not only possess charge, but also a quantum mechanical spin. The spin provides an additional degree of freedom that can be exploited in devices to realize a host of new spintronic

technologies, from. nonvolatile "instant-on" computers to so-called "reconfigurable logic" elements whose underlying circuitry can be changed on-the-fly.

The research was conducted by Dr. Steven Erwin, Dr. Michael Haftel, and Dr. Alexander Efros from NRL's Materials Science and Technology Division; Dr. Thomas Kennedy from NRL's Electronics Science and Technology Division; and Ms. Lijun Zu and Professor David Norris from the Department of Chemical Engineering and Materials Science at the University of Minnesota. The Office of Naval Research and the National Science Foundation provided funding for the research.

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