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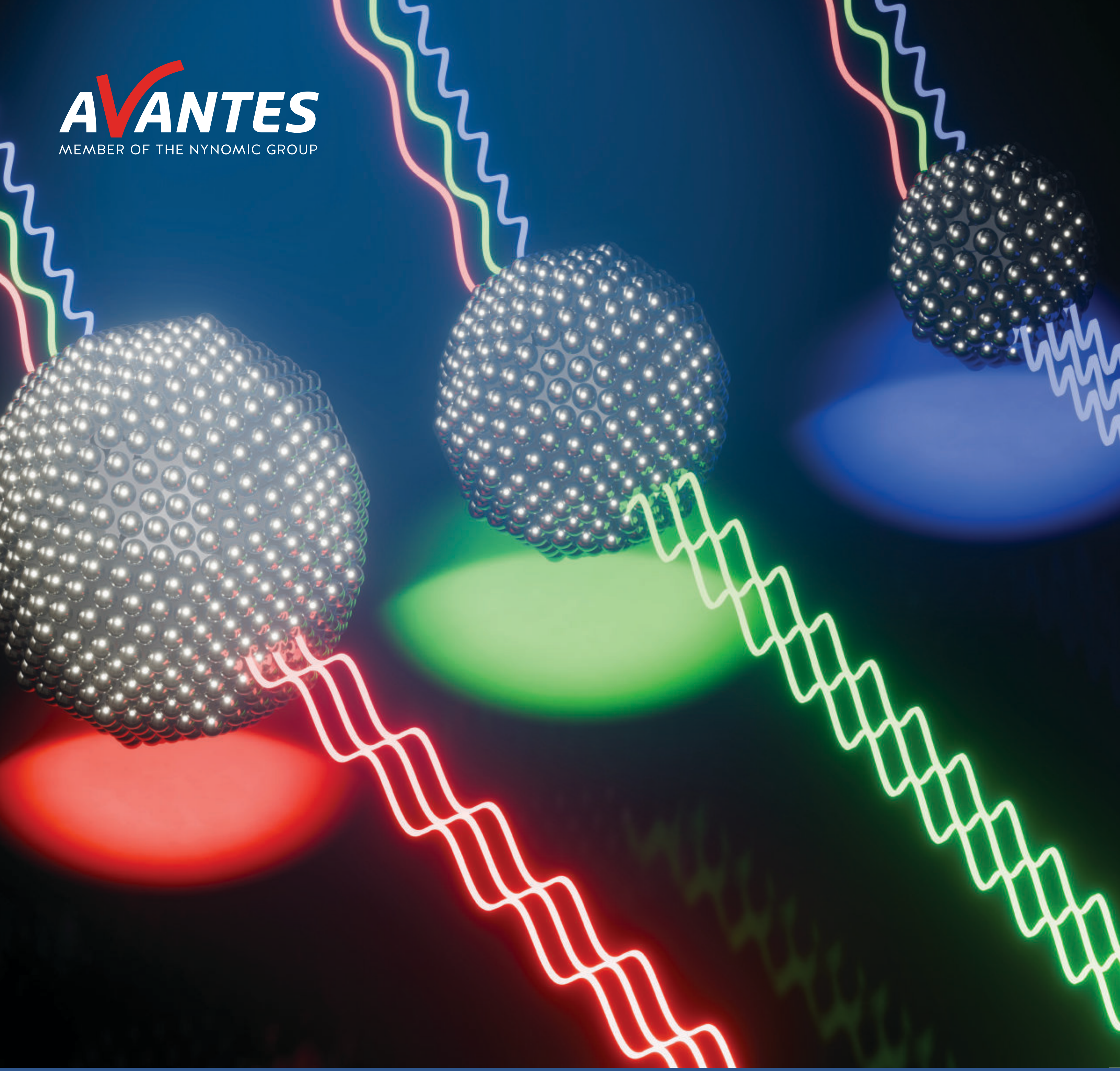
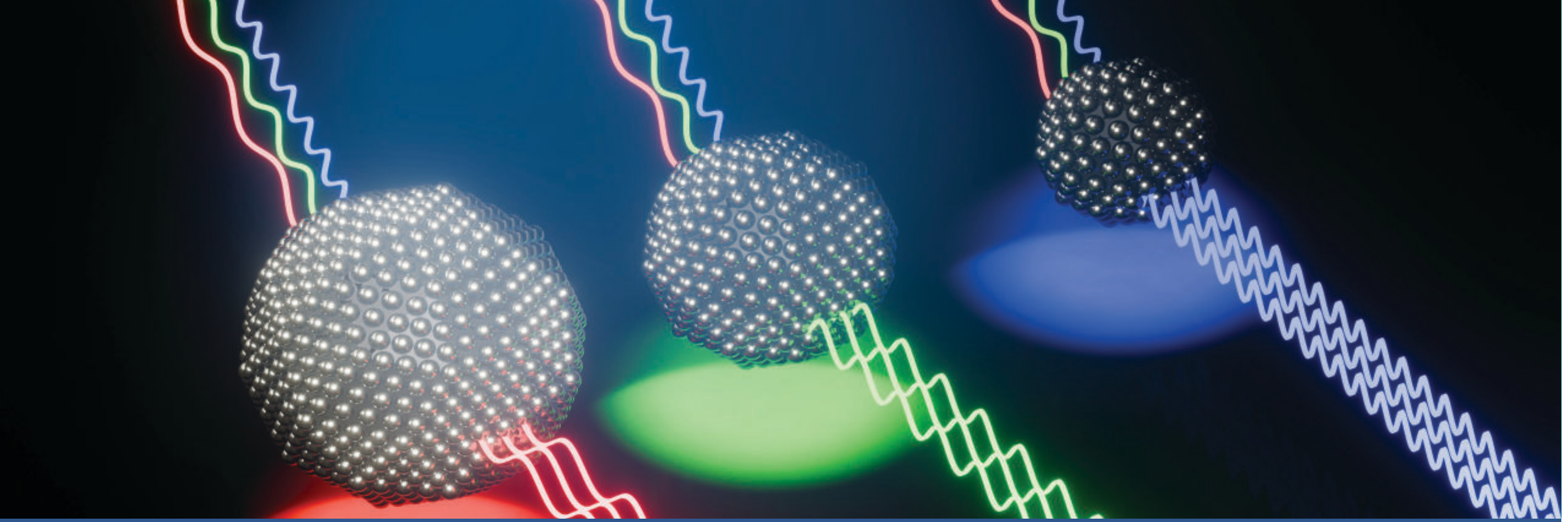


ARTICLE

ADVANCES IN CARBON QUANTUM DOTS: SYNTHESIS, APPLICATIONS, AND SPECTRAL ANALYSIS WITH AVANTES SPECTROMETERS



INTRO

ADVANCES IN CARBON QUANTUM DOTS: SYNTHESIS, APPLICATIONS, AND SPECTRAL ANALYSIS WITH AVANTES SPECTROMETERS

Over the past four decades, quantum dots have evolved from a scientific curiosity into a cornerstone of modern nanotechnology, finding applications across a wide array of fields, including biotechnology, electronics, and energy. Among these, carbon quantum dots (CQDs) have garnered significant attention due to their unique properties, such as tunable fluorescence, biocompatibility, and environmentally friendly synthesis. Unlike traditional semiconductor quantum dots, which often pose toxicity concerns, carbon quantum dots offer a safer alternative, opening new possibilities in biomedical imaging, drug delivery, and sustainable energy solutions.

As research in this area progresses, the ability to precisely characterize and control the optical properties of carbon quantum dots has become increasingly important. This is where spectroscopy plays a crucial role. Through advanced spectroscopic techniques, researchers can gain deeper insights into the emission profiles, structural properties, and chemical compositions of carbon quantum dots. These insights not only facilitate the development of new applications but also ensure the consistency and scalability required for commercial adoption.

This application note explores the latest advancements in carbon quantum dots, from their synthesis and surface engineering to their wide-ranging applications in nanotechnology and energy.
We will also delve into the critical role of spectroscopy in understanding and optimizing these materials, demonstrating how Avantes spectrometers can support researchers and manufacturers in harnessing the full potential of carbon quantum dots.

INTRODUCTION

Traditional quantum dots are simply individual semiconductor nanocrystals where quantum confinement effects can be utilized to tune their fluorescence emission profiles. In the case of bulk semiconductors (i.e., LEDs and laser diodes), the minimum energy required to excite an electron to the conduction band and, subsequently, energy released through electron-hole recombination is dictated by material composition. However, when an electron-hole pair, referred to jointly as an exciton, is confined within a space commensurate with the de Broglie wavelength, which is typically on the order of 10 nm at room temperature. It behaves as a "particle in a box." This process, known as quantum confinement, causes the bandgap energy and therefore, the emission wavelength to change as a function of particle size. Building off the energy levels of a particle in an infinite square well potential (aka particle in a box) $E_n = \frac{h^2 n^2}{8mL^2}$ where n is the energy level, ***h*** is Plank's constant, ***m*** is the particle's mass, and ***L*** is the width of the well. The emission wavelength λ can be determined using,

$$\lambda = \frac{hc}{E_{g,bulk} + \frac{h^2}{8r^2}\left(\frac{1}{m_e^*} - \frac{1}{m_h^*}\right)}.$$

In Equation 1 ***c*** represents the speed of light, $E_{g,bulk}$ the band gap energy of the bulk semiconductor, ***r*** is the radius of the quantum dot, m_e^* the effective mass of the electron and m_h^* is the effective mass of the hole. Based on this relationship, as the size of the dot decreases, so too does the emission wavelength, providing an exceptionally high degree of control over the emission wavelength, as shown schematically in Figure 1. It should also be noted that m_e^* and m_h^* are not the actual masses of the particles (holes have no mass); instead, they are related to the curvature of the energy-momentum relationship, which plays the equivalent role of the mass of a particle in a box. However, these values are extremely well characterized and can simply be looked up for a particular material. For example, in CdSe nanocrystals that m_e^* and m_h^* are 0.13 and 0.45 times the mass of an electron, and 0.07 and 0.50 times the mass of an electron, respectively in bulk GaAs.

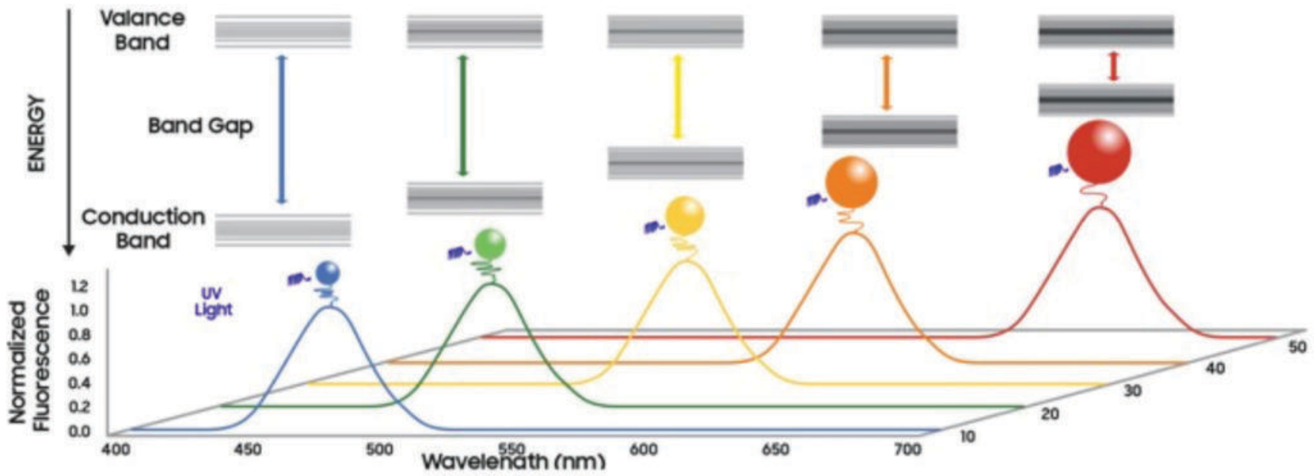


FIGURE 1: *Schematic Illustration of the relationship between quantum dot, size, bandgap and emission spectra.*

THE RISE OF QUANTUM DOTS

The high tunability, quantum yield, and narrow linewidth make quantum dots highly desirable as fluorescent tags, particularly for in vivo diagnostics. However, it is undesirable to inject II-VI semiconductors such as CdSe into human patients due to the potential toxicity. Fortunately, in 2004 Xiaoyou Xu and others at the University of South Carolina produced "Fluorescent Single-Walled Carbon Nanotube Fragments," which we now understand to be carbon quantum dots[1]. Driven mainly by a combined desire for biocompatibility and greener synthesis techniques over the last 20 years, there has been an explosion in carbon dot research. In fact, it has recently been shown that carbon dots can be synthesized from nearly any organic material ranging from orange juice[2] to upcycled polypropylene[3]. There is even recent evidence showing that carbon dots are produced (and inhaled) from electronic cigarettes[4].

CARBON DOTS SYNTESIS AND APPLICATIONS

Carbon dots are produced through hydrothermal treatment of any carbon-containing material. While this is typically done in an autoclave, it can also be done through laser ablation of carbon in solution. Researchers at the Universities of Messina and Enna have recently created carbon dots by focusing a 350mJ pulsed 970nm laser with a 10Hz repetition rate into a solution of charcoal dissolved in phosphate-buffered saline (PBS)[5]. Using an Avantes AvaSpec-2048-USB2 spectrometer (now available as AvaSpec-ULS2048CL-EVO) and a 365nm UV emission lamp they were able to demonstrate blue fluorescence with a spectral peak at 478 nm, as shown in figure 2.

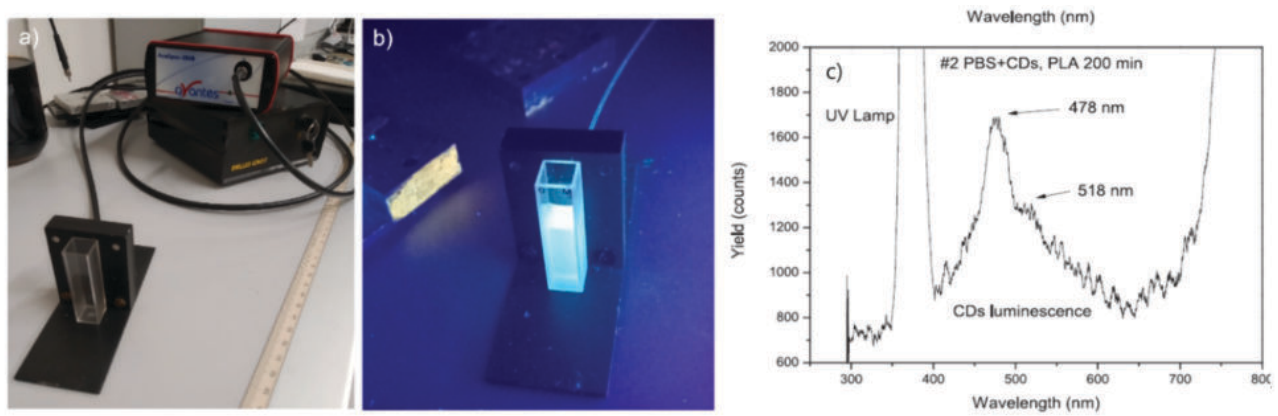


FIGURE 2: *Experimental set-up luminescent under UV illumination (b), and emission spectrum when excited at 365 nm(c).*[5]

These impurities can further complicate the HOMO-LUMO structure, leading to greater absorption and emission wavelength inexactness. However, this feature can also be utilized judiciously to tune the emission wavelength. For example, in a study published this summer (2024), a collaboration between the University of Munich, Trieste, and Leiden yielded blue-emitting boron- and nitrogen-doped carbon dots.[7] By incorporating these dots into thin-films, they were able to produce extremely bright white light emitting electrochemical cells with quantum yields of 42%. To verify the coatings' photostability and conversion efficiency, the electro-luminescence spectra were measured using an Avaspec-2048-USB2 coupled with an AvaSphere 30-Irrad Integrated sphere.

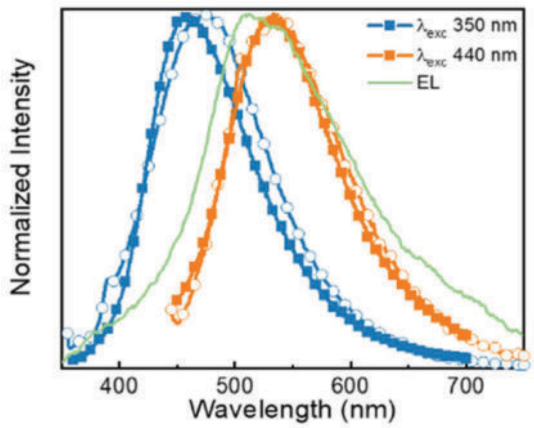


FIGURE 3: *Normalized emission intensity of boron- and nitrogen-doped carbon dots excited at of 350 nm (blue) and 440 nm (orange) and the electro luminescence spectrum (green).*[7]

Another particularly interesting use case was the recent collaboration between the Universities of Palermo and Messina in Italy, which demonstrated the ability to use microporous poly(D,L-lactide) acid–carbon nanodot (PLA-CD) nanocomposite scaffolds for image-guided bone regeneration.[6] In this work, they were able to quantify the amount of carbon dots successfully incorporated into the scaffolding by using an Avantes AvaSpec-ULS2048CL-EVO with a dual halogen-deuterium light source to monitor absorbance at 450nm and comparing it to a calibration curve produced by dissolving the dots in dichloromethane.

FUTURE APPLICATIONS USING CARBON DOTS

Carbon quantum dots are poised to transform a wide variety of scientific applications. For example, their biocompatibility, low toxicity, and eco-friendliness make them particularly appealing for biomedical applications, including bioimaging and drug delivery.

Carbon dots are currently being used in several clinical trials mainly in oncology, where photoactive drugs are functionalized with carbon dots, enabling the targeted delivery of photodynamic therapies. They have also been demonstrated as a means of gene delivery and treating neurological disorders.

Furthermore, the recent advancements in the synthesis of carbon dots provide precise control over their emission spectra, opening doors to their use in light-emitting diodes (LEDs) and photovoltaics. The ability to fine-tune their emission spectra through doping and surface engineering has further expanded their utility in creating more efficient solar cells and white light-emitting diodes.

They also can be used in energy storage by enhancing specific capacitance, energy density, and durability. Early work in osmotic power generation even hints at a future where carbon dots could play a pivotal role in sustainable energy solutions.

THE RISE OF QUANTUM DOTS

While commercial applications of carbon dots are still in the nascent phase, ongoing research is focused on overcoming challenges such as scalability and integration into existing technologies. As these hurdles are addressed, carbon dots will lead to breakthroughs in sensors, electronics, and environmental applications, marking them as a cornerstone in the future of nanotechnology. Avantes spectrometers are ideally suited to help facilitate these developments, particularly as production volumes increase, requiring large-scale batch analysis of absorption and emission spectra.

It is also important to note that all of Avantes spectrometers are available as desktop or OEM modules which can be integrated as subsystems. Avantes also offers multichannel rack mount systems which feature up to 10 spectrometer channels in a single housing and these can be use in quality control systems. Avantes spectrometers are available with USB, SPI, RS232 and Ethernet communication options, and they include native digital & analog input/output capabilities to provide for a easy interface with other devices.

Additionally, the Avantes AvaSpec DLL SDK package, with sample programs in Delphi, Visual Basic, C#, C++, LabView, MatLab, Python and many other programming environments, enables users to develop their own code.

For more information about the full range of spectrometer options available from Avantes for absorption spectroscopy, please feel free to visit the website at www.avantes.com or give us a call at +1 (303)-410-8668 where our knowledgeable applications specialists are standing by to help.

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