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Recent advances in germanium nanocrystals: Synthesis, optical properties and applications

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ABSTRACT

Germanium nanocrystals (Ge NCs) have recently attracted renewed scientific interest as environmentally friendlier alternatives to classical II–VI and IV–VI QDs containing toxic elements such as Hg, Cd and Pb. Importantly, Ge NCs are nontoxic, biocompatible, and electrochemically stable. An essential requirement is the ability to prepare Ge NCs with narrow size distributions and well characterized surface chemistry, as these define many of their photophysical properties. However, a thorough discussion on these criteria has not been achieved to date. Here, size, surface control, and mechanisms for light emission in Ge NCs are discussed and their exciting recent applications are highlighted. The beneficial properties of Ge NCs suggest that this material can improve the performance of numerous devices like solar cells, photodetectors, and lithium ion batteries.

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1. Introduction

Semiconductor nanocrystals (NCs) or quantum dots (QDs) have been the focus of extensive research due to their unique size-dependent optical and electrical properties [1,2]. A great deal is now known about methods to control their size, shape, composition and surface chemistry [3–5] allowing for applications in a wide range of areas such as light emitting devices [6], solar cells [7], phosphors [8], field effect transistors [9], sensing [10] and biological imaging [11,12] (see Fig. 1). While these II–VI (e.g. CdX, X = Se, S, Te), III–V (e.g. InP, InAs, GaAs) and IV–VI (e.g. PbX, X = Se, S,) materials offer broad absorption profiles, facile spectral tuning, high quantum yields, long fluorescence lifetimes and good photochemical stability [13], legitimate concerns have been raised regarding their toxicity [14]. Derfus et al. confirmed that QDs with a CdSe core and without a ZnS shell were toxic to liver cells after exposure to UV light [15]. It was shown that QDs build up in vital organs for at least 90 days once inside the body [16]. Moreover, the European Union's Restriction of Hazardous Substances Directive severely limits the use of heavy metal cations such as Cd, Pb and Hg in consumer electronics [17]. Hence, it is important to develop alternative QDs with good optical and electrical properties but composed of materials with low toxicities. Consequently, research has concentrated on the advancement of heavy metal free alternatives including Group IV materials and ternary I–III–VI alloys [14].

Germanium nanocrystals were discovered 35 years ago, in 1982 by Hayashi et al. [23], and even though they were termed "microcrystals", their size regime and size dependent optical properties alluded to the fact that they were indeed nanocrystals. Since then, and particularly in the last 4 years germanium nanocrystals have attracted renewed attention as environmentally friendlier alternatives to classical compound semiconductor nanocrystals as they are nontoxic, biocompatible, electrochemically stable and compatible with current microelectronics. Ge is especially appealing due to the higher electron

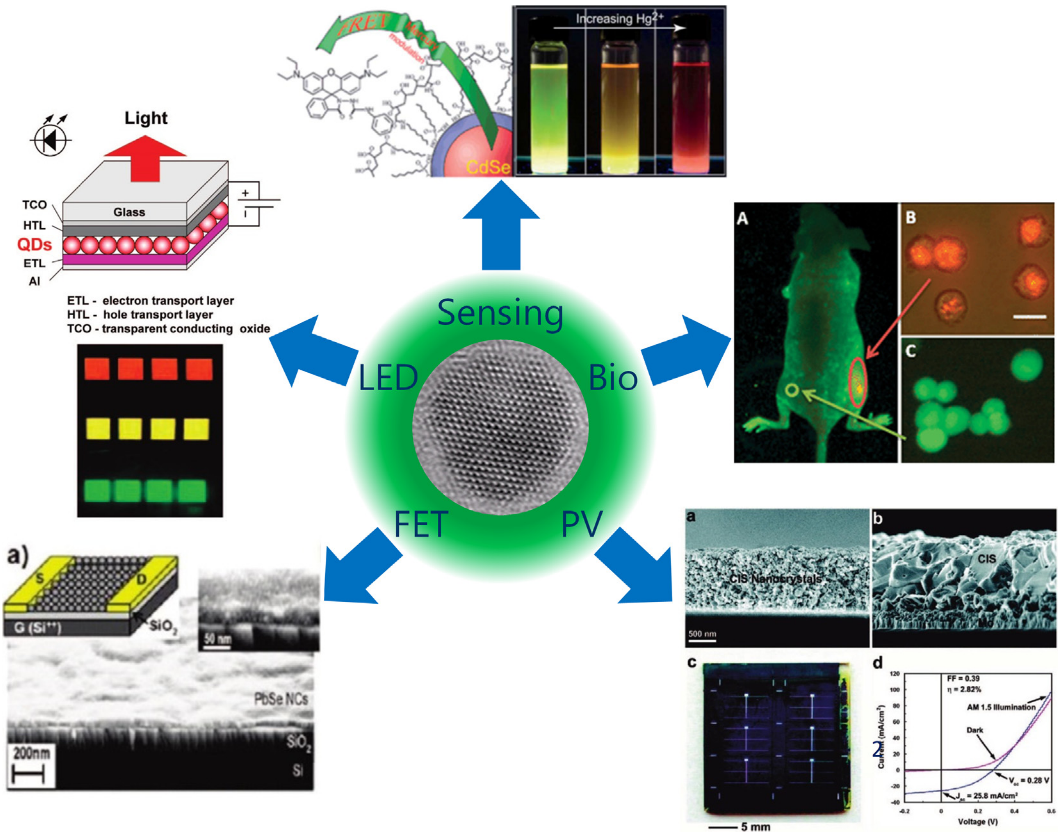

Fig. 1. Overview of the many uses for classical quantum dots. Reproduced with permission from Refs. [18–22] and *Chem Rev* **110**, 2010, 389, DOI: 10.1021/cr900137k, Copyright © 2009 American Chemical Society.

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