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Nanocrystals in the Strong Coupling Regime Engineering New Materials from the Nanoscale

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14. ABSTRACT
Nanomaterials are defined by their shape, size, material, structure, and they offer the opportunity to tailor materials properties in ways that are distinctly different from the bulk materials from which they are derived. However, to make practical materials with novel functionality, these materials must be joined in a way that preserves these novel properties while combining them with others from dissimilar materials. The goal of this project was to develop, measure, and model motifs to couple these nanocrystalline materials and thereby unlock the combinatorial complexity of this chemical space.

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Nanocrystals in the Strong Coupling Regime: . Engineering New Materials from the Nanoscale

Final Report

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Nanomaterials are defined by their shape, size, material, structure, and they offer the opportunity to tailor materials properties in ways that are distinctly different from the bulk materials from which they are derived. However, to make practical materials with novel functionality, these materials must be joined in a way that preserves these novel properties while combining them with others from dissimilar materials. The goal of this project was to develop, measure, and model motifs to couple these nanocrystalline materials and thereby unlock the combinatorial complexity of this chemical space. In this regard, it is our vision that these "designer atoms" will permits materials with complexity and variation that will far surpass traditional materials, but only if we understand how to link the nanoparticles together such that electronic motion among the particles becomes correlated just as electrons in simple molecules are correlated. Unlike discrete atoms, however, nanoparticles are continuously variable. The possibilities are limitless.

Our project has combined inorganic synthesis of linked nanoparticles, ultrafast spectroscopy of coherent coupling, and theoretical calculations of long-range electronic correlation to create and to optimize linkages between nanocrystal "building blocks" to permit construction of new materials.

Major advances include:

1. Determining the Band Filling of Cadmium Telluride Polymers in Quantum Dots (in collaboration with co-PI Dmitri Talapin):

Related publication acknowledging AFOSR support:
Valentine, A. J. S., Talapin, D. V. & Mazziotti, D. A. Orbitals, Occupation Numbers, and Band Structure of Short One-Dimensional Cadmium Telluride Polymers. J Phys Chem A 121, 3142-3147, (2017).

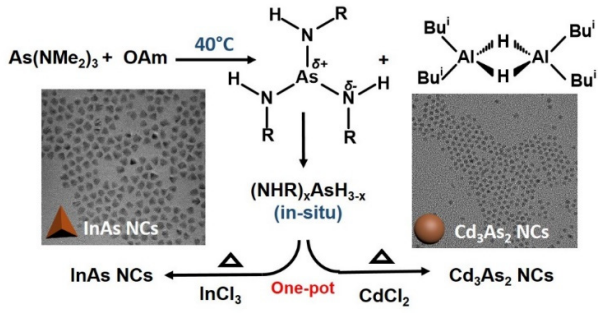
Recent work found that soldering CdTe quantum dots together with a molecular CdTe polymer yielded field-effect transistors with much greater electron mobility than quantum dots alone. We present a computational study of the CdTe polymer using the active-space variational two-electron reduced density matrix (2-RDM) method. While analogous complete active-space self-consistent field (CASSCF) methods scale exponentially with the number of active orbitals, the active-space variational 2-RDM method exhibits polynomial scaling. A CASSCF calculation using the (48o,64e) active space studied in this paper requires 10^{24} determinants and is therefore intractable, while the variational 2-RDM method in the same active space requires only 2.1×10^7 variables. Natural orbitals, natural-orbital occupations, charge gaps, and Mulliken charges are reported as a function of polymer length. The polymer, we find, is strongly correlated, despite possessing a simple sp3-hybridized bonding scheme. Calculations reveal the formation of a nearly saturated valence band as the polymer grows and a charge gap that decreases sharply with polymer length.

2. Facile, Economic and Size-Tunable Synthesis of Metal Arsenide Nanocrystals.

Related publication acknowledging AFOSR support:
Srivastava, V.; Janke, E. M.; Diroll, B. T.; Schaller, R. D.; Talapin, D. V. Chem. Mater. 2016, 28, 6797-6802.

Synthesis of colloidal nanocrystals (NC) of important arsenide nanomaterials (e.g. InAs, Cd_3As_2) has been limited by the lack of convenient arsenic precursors. Here we address this constraint by identifying a convenient and commercially available As precursor, tris-dimethylaminoarsine ($As(NMe_2)_3$), which can be used to prepare high quality InAs NCs with controlled size distributions. Our approach employs a reaction between $InCl_3$ and $As(NMe_2)_3$ using diisobutylaluminum hydride (DIBAL-H) to convert $As(NMe_2)_3$ *in situ* into reactive intermediates $AsHx(NMe_2)_{3-x}$ where x=1,2,3. NC size can be varied by changing DIBAL-H concentration and growth temperature, with colloidal solutions of InAs showing size dependent absorption and emission features tunable across wavelengths of 750-1450 nm. We also show that this approach works well for the colloidal synthesis of Cd_3As_2 NCs. By circumventing the preparation

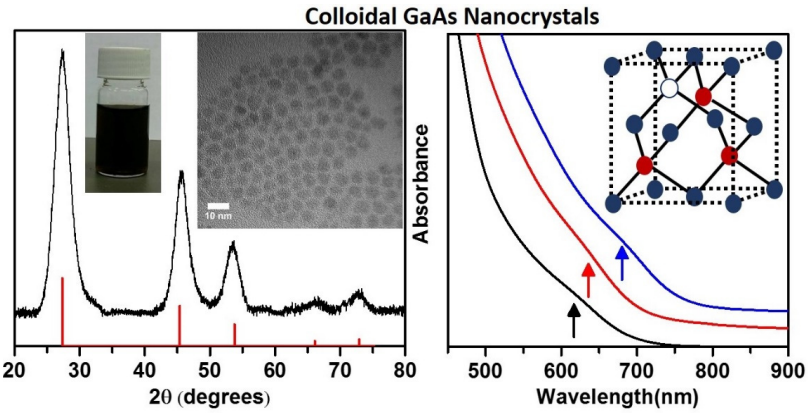
of notoriously unstable and dangerous arsenic precursors (e.g. AsH_3 and $As(SiMe_3)_3$), this work improves the synthetic accessibility of arsenide-based NCs and, by extension, the potential of such NCs for use in infrared (IR) applications such as communications, fluorescent labeling and photon detection.



3. Investigation and curing structural defects in colloidal GaAs quantum dots.

Related publication acknowledging AFOSR support:
Srivastava, V.; Liu, W.; Janke, E. M.; Kamysbayev, V.; Filatov, A. S.; Sun, C.-J.; Lee, B.; Rajh, T.; Schaller, R. D.; Talapin, D. V. Nano Lett. 2017, 17 (3), 2094-2101.

GaAs is arguably the most important member of the III-V semiconductor family due to its excellent electronic and optical properties. The direct band gap, high electron mobility and saturation electron velocity, reliable p-type and n-type doping make GaAs a material of choice for top performing solar cells, transistors, lasers and LEDs. However, colloidal GaAs nanocrystals remain largely unexplored because of the difficulties with their synthesis. Traditional synthetic routes either fail to produce pure GaAs phase or result in materials whose optical properties are very different from the behavior expected for quantum dots of direct-gap semiconductors. In this work, we demonstrate a variety of synthetic routes toward crystalline GaAs NCs (left panel). By using a combination of Raman, EXAFS, transient absorption, and EPR spectroscopies, we conclude that unusual optical properties of colloidal GaAs NCs can be related to the presence of Ga vacancies and lattice disorder. These defects do not manifest themselves in TEM images and powder X-ray diffraction patterns but are responsible for the lack of absorption features even in apparently crystalline GaAs nanoparticles. We introduce novel molten salt based annealing approach to alleviate these structural defects and show the emergence of size-dependent excitonic transitions in colloidal GaAs quantum dots (right panel).



4. Computing Molecular Conductivity with Increased Accuracy:

Related publication acknowledging AFOSR support:
Sajjan, M. & Mazziotti, D. A. Current-Constrained Density-Matrix Theory to Calculate Molecular Conductivity with Increased Accuracy. Commun Chem 1, DOI: 10.1038/s42004-42018-40030-42002, (2018).

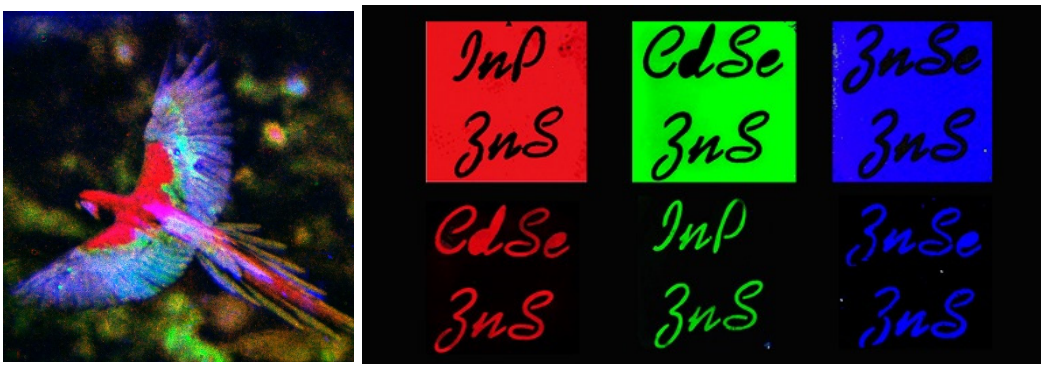
Molecular conductivity is the quantum flow of electrons through a molecule. Since its conception by Aviram and Ratner, molecular conductivity has been realized experimentally in molecules and molecular-scale circuits. Significant challenges, however, remain for its prediction with popular theoretical methods often overpredicting conductance by as much as an order of magnitude. Here we report a current-constrained, electronic structure-based variational principle for molecular conductivity. Unlike existing theories, which set the voltage to compute the current, the current-constrained variational principle determines the voltage from an electronic structure calculation in which the current is added as a constraint. We apply the variational principle to benezenedithiol with gold and nickel leads where it matches experimental values and trends, improving upon previous theory by as much as 1–2 orders of magnitude. The current constraint produces a conducting steady state that includes all many-body effects treatable by the electronic structure calculation.

Press Release: https://news.uchicago.edu/story/less-more-when-it-comes-predicting-molecules-conductivity

5. Direct Optical Lithography of Nanocrystals

Related publication acknowledging AFOSR support:
Wang, Y. Y., Fedin, I., Zhang, H. & Talapin, D. V. Direct Optical Lithography of Functional Inorganic Nanomaterials. Science 357, 385-388, (2017).

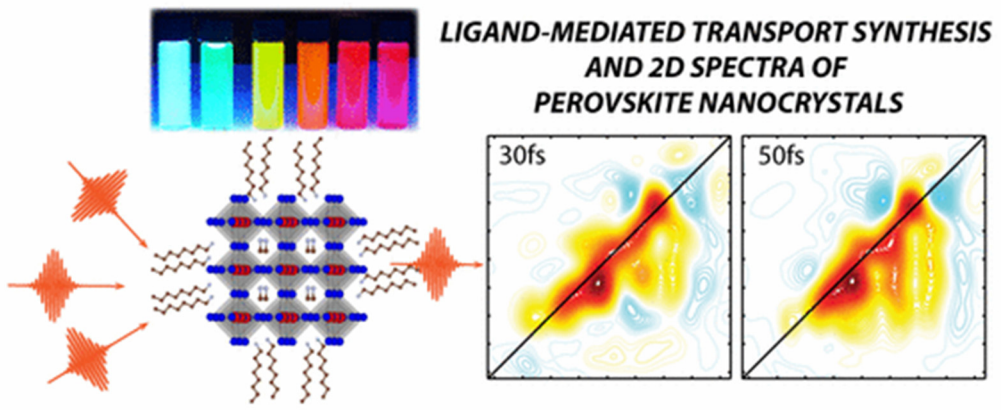
Existing lithorgraphy methods, such as photolithography, were originally developed for silicon wafers and do not work particularly well for nanomaterials patterning. Our work has addressed this important missing piece. We introduced a general approach for Direct Optical Lithography of Functional Inorganic Nanomaterials (DOLFIN), which gives us the ability to pattern nanomaterials (metals, semiconductors, dielectrics, and magnets) with high precision, throughput, and fidelity. No organic impurities are present in the patterned layers, which helps achieve excellent electronic and optical properties. The conductivity, carrier mobility, dielectric, and luminescence properties of DOLFIN-patterned layers are on par with the properties of state-of-the-art solution-processed electronic materials. I am not aware of any previous work along similar lines and believe that our report will boost progress for a range of QD technologies. Direct optical lithography of functional inorganic nanomaterials (DOLFIN) makes different nanomaterials directly into "ink" in a process that bypasses the need to lay down a polymer stencil. Using a series of optically active ligands, light effectively causes the nanocrystals to fall out of solution and be lithographically deposited on a substrate. Using successive deposition or ligands sensitive to different wavelengths, different materials can be co-deposited.



6. Industrially scalable perovskite synthesis using ligand-mediated transport

Related publication acknowledging AFOSR support:
Wang, L. L., Williams, N. E., Malachosky, E. W., Otto, J. P., Hayes, D., Wood, R. E., Guyot-Sionnest, P. & Engel, G. S. Scalable Ligand-Mediated Transport Synthesis of Organic-Inorganic Hybrid Perovskite Nanocrystals with Resolved Electronic Structure and Ultrafast Dynamics. Acs Nano 11, 2689-2696, (2017).

A novel synthetic approach using ligands to both solubilize precursors and cap nanoparticles has enable scalable synthesis of extremely stable perovskite quantum dot, direct access to mixed halide quantum dots (previously only accessible by ligand exchange), and processing under environmental conditions. The dots show fluorescence yields as high as 97%. The photoluminescence is directly tunable across the entire visible region.



7. Calculating Strong Electron Correlation in Nitrogenase Cofactor, FeMoco:

Related publication acknowledging AFOSR support:
Montgomery, J. M. & Mazziotti, D. A. Strong Electron Correlation in Nitrogenase Cofactor, Femoco. J Phys Chem A 122, 4988-4996, (2018).

FeMoco, $MoFe_7S_9C$, has been shown to be the active catalytic site for the reduction of nitrogen to ammonia in the nitrogenase protein. An understanding of its electronic structure including strong electron correlation is key to designing mimic catalysts capable of ambient nitrogen fixation. Active spaces ranging from [54, 54] to [65, 57] have been predicted for a quantitative description of FeMoco's electronic structure. However, a wave function approach for a singlet state using a [54, 54] active space would require 10^{29} variables. In this work, we systematically explore the active-space size necessary to qualitatively capture strong correlation in FeMoco and two related moieties, $MoFe_3S_7$ and Fe_4S_7, using CASSCF and 2-RDM methods. These are the first *ab initio* calculations of FeMoco.

8. Disentangling Quantum Molecules with External Fields:

Related publication acknowledging AFOSR support:
Sajjan, M., Head-Marsden, K. & Mazziotti, D. A. Entangling and Disentangling Many-Electron Quantum Systems with an Electric Field. Phys Rev A 97, 062502, (2018).

We show that the electron correlation of a molecular system can be enhanced or diminished through the application of a homogeneous electric field antiparallel or parallel to the system's intrinsic dipole moment. More generally, we prove that any external stimulus that significantly changes the expectation value of a one-electron operator with nondegenerate minimum and maximum eigenvalues can be used to control the degree of a molecule's electron correlation. Computationally, the effect is demonstrated in HeH^+, MgH^+, BH, HCN, H2O, HF, formaldehyde, and a fluorescent dye. Furthermore, we show in calculations with an array of formaldehyde

(CH_2O) molecules that the field can control not only the electron correlation of a single formaldehyde molecule but also the entanglement among formaldehyde molecules. The quantum control of correlation and entanglement has potential applications in the design of molecules with tunable properties and the stabilization of qubits in quantum computations.

9. Mapping energy transfer across complex 2D networks

Related publication acknowledging AFOSR support:
Dahlberg, P. D., Ting, P. C., Massey, S. C., Allodi, M. A., Martin, E. C., Hunter, C. N. & Engel, G. S. Mapping the Ultrafast Flow of Harvested Solar Energy in Living Photosynthetic Cells. Nat Commun 8, 988, (2017).

We developed a new approach to simultaneously measure transport rates from 2D electronic spectroscopy while exploiting annihilation dynamics to measure network conductivity and organization of photosynthetic light harvesting membranes *in vivo*. The dataset proves extremely sensitive to topology and organization within the membrane and can reliably constrain the size of the functional photosynthetic unit, the size of the LH1 island, and the transport times between all pairs of light harvesting complexes in a single dataset.In principle, the same approach should be useful to measure transport in materials created by DOLFIN processing.

10.Predicting Ligand Non-innocence through Quantum Entanglement:

Related publication acknowledging AFOSR support:
McIsaac, A. R. & Mazziotti, D. A. Ligand Non-Innocence and Strong Correlation in Manganese Superoxide Dismutase Mimics. Phys Chem Chem Phys 19, 4656-4660, (2017).

We examine the recently reported first synthesis of the elusive low-valent vanadium(III) in a vanadium oxo complex with a computation representing 10^{21} quantum degrees of freedom. While this computation is intractable with a conventionally constructed wave function, it is performed here by a direct calculation of the system's two-electron reduced density matrix (2-RDM), where the 2-RDM is constrained by nontrivial conditions, known as *N*-representability conditions, which restrict the 2-RDM to represent an *N* electron quantum system. We show that the added (reducing) electron becomes entangled among the five pyridine ligands. While smaller calculations predict a metal-centered addition, large-scale 2-RDM calculations show that quantum entanglement redirects the electron transfer to the pyridine ligands, resulting in a ligand-centered addition. Beyond its implications for the synthesis of low-valent vanadium oxo complexes, the result suggests new possibilities for using quantum entanglement to predict and control electron transfer in chemical and biological materials.

11. Identifying Long-range Order in Materials from a Cumulant Density-matrix Theory:

Related publication acknowledging AFOSR support:
Raeber, A. & Mazziotti, D. A. Large Eigenvalue of the Cumulant Part of the Two-Electron Reduced Density Matrix as a Measure of Off-Diagonal Long-Range Order. Phys Rev A 92, 052502, (2015).

Off-diagonal long-range order (ODLRO) in the two-electron reduced density matrix (2-RDM) has long been recognized as a mathematical characteristic of conventional superconductors. The large eigenvalue of the 2-RDM has been shown to be a useful measure of this long-range order. The 2-RDM can be represented as the sum of a connected (cumulant) piece and an unconnected piece. In this work, we show that the cumulant 2-RDM also has a large eigenvalue in the limit of ODLRO. The largest eigenvalue of the cumulant 2-RDM, we prove, is bounded from above by *N*. In the limit of extreme pairing, such as Cooper pairing, the largest eigenvalue approaches its extreme values of *N*. The large eigenvalue of the cumulant 2-RDM, we show, implies the large eigenvalue of the 2-RDM and, hence, is a natural measure of ODLRO that vanishes in the mean-field limit. While the present results are directly applicable to theoretical and computational studies of long-range order in phenomena like superconductivity, they are also applicable to the study of more general materials with long-range order behavior. Copper oxide compounds, for example, have a high-temperature state referred to as a pseudogap metal which has both simple metallic character and long-range quantum entanglement. The model Hamiltonians studied in this work show that a continuous curve of largest cumulant 2-RDM eigenvalues can be generated in the range from 0 to N, with 0 being the mean-field limit and N being the extreme AGP (superconducting) limit. Similarly, materials can have large cumulant 2-RDM eigenvalues that indicate a degree of long-range order between that of a typical insulating material and that of a superconductor. The indicators for ODLRO, developed here, provide tools for exploring more fully the spectrum of quantum long-range order in molecular systems and materials

12. Computing Strongly Correlated Molecules in Polynomial Time:

Related publication acknowledging AFOSR support:
Mazziotti, D. A. Enhanced Constraints for Accurate Lower Bounds on Many-Electron Quantum Energies from Variational Two-Electron Reduced Density Matrix Theory. Phys Rev Lett 117, 153001, (2016).

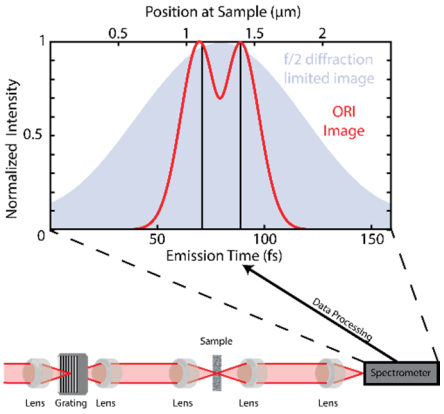
A central challenge of physics is the computation of strongly correlated quantum systems. The past ten years have witnessed the development and application of the variational calculation of the two-electron reduced density matrix (2-RDM) without the wave function. We developed an orders-of-magnitude improvement in the accuracy of 2-RDM calculations without an increase in

their computational cost. The advance is based on a low-rank, dual formulation of an important constraint on the 2-RDM, the T2 condition. Calculations are presented for metallic chains and a cadmium-selenide dimer. The low-scaling T2 condition will have significant applications in atomic and molecular, condensed-matter, and nuclear physics.

13. Optical Resonance Imaging

Related publication acknowledging AFOSR support:
Allodi, M. A., Dahlberg, P. D., Mazuski, R. J., Davis, H. C., Otto, J. P. & Engel, G. S. Optical Resonance Imaging: An Optical Analog to Mri with Subdiffraction-Limited Capabilities. Acs Photonics 3, 2445-2452, (2016).

An optical analog to MRI was invented to enable sub-diffraction limited spatial resolution, femtosecond time resolution, and spectral resolution. In essense, we use pulse front tilt to map space to time and then measure *when* a stimulated emission photon appears rather than where it came from – this is in direct analogy to how MRI maps space to energy and monitors the frequency of the RF photon. Indeed, energy and time are Fourier conjugates and both operate outside the Abbe diffraction limit. We estimate that this approach can beat the diffraction limit by about a factor of 10. The tomographic method is inherently widefield, coherent, and phase-sensitive. It will have application in semiconductors, light harvesting systems, and nanoparticle arrays.

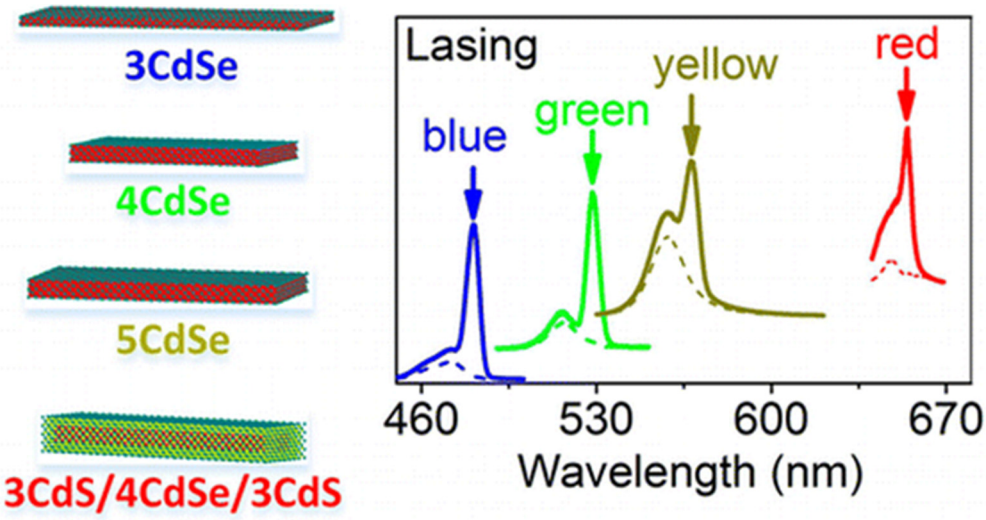


14. Lasing from Stacked Arrays of Nanoplatelets

Related publication acknowledging AFOSR support:
She, C. X., Fedin, I., Dolzhnikov, D. S., Dahlberg, P. D., Engel, G. S., Schaller, R. D. & Talapin, D. V. Red, Yellow, Green, and Blue Amplified Spontaneous Emission and Lasing Using Colloidal Cdse Nanoplatelets. Acs Nano 9, 9475-9485, (2015).

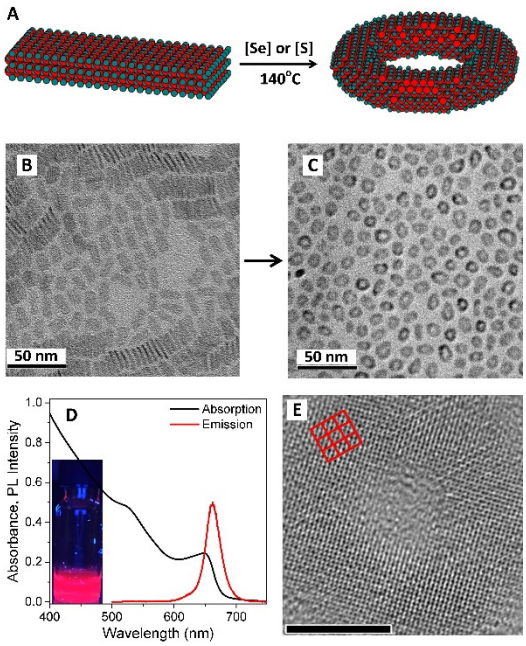
We observed lasing from stacked arrays of CdSe nanoplatelets with extraordinarily low thresholds. In addition, these nanoplatelet lasers can be tuned across the "green hole" where traditional diode lasers do not exist. Specifically, we show that colloidal nanoplatelets (NPLs)

with electronic structure of quantum wells can produce amplified spontaneous emission in the red, yellow, green, and blue regions of the visible spectrum with low thresholds and high gains. For blue-emitting NPLs, the ASE threshold is 50 μJ/cm2, lower than any reported value for nanocrystals. By varying the thickness (not the material), we demonstrate red, yellow, green, and blue lasing. We find that the lateral size of NPLs does not show any strong effect on the Auger recombination rates and, correspondingly, on the ASE threshold or gain saturation. This observation highlights the qualitative difference of multiexciton dynamics in CdSe NPLs and other quantum-confined CdSe materials, such as quantum dots and rods. Our measurements of the gain bandwidth and gain lifetime further support the prospects of colloidal NPLs as solution-processed optical gain materials.



15.First synthesis of colloidal CdSe Quantum Rings.

Related publication acknowledging AFOSR support:
Fedin, I. & Talapin, D. V. Colloidal Cdse Quantum Rings. J Am Chem Soc 138, 9771-9774, (2016)..



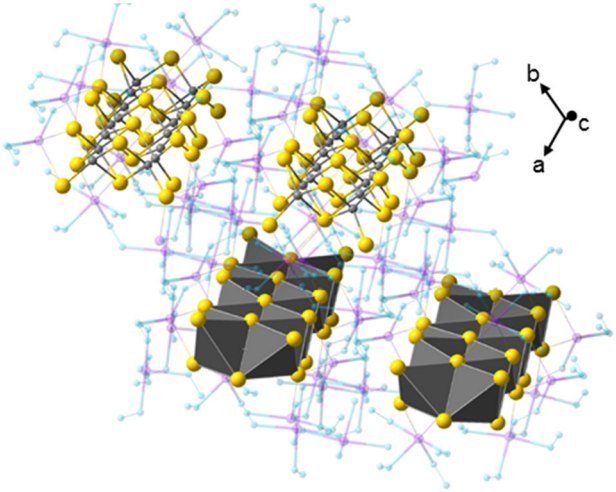
Precise engineering of size, shape, and composition of nanoscale crystals is required to fully exploit and utilize optical, electronic, magnetic, and catalytic properties across a broad range of nanomaterials. In the case of semiconductor nanostructures, the relation between the geometry (i.e., size and shape) and the electronic structure is encoded in quantum confinement: the nanocrystal surface serves as a boundary to confine the electron and hole wave functions. We developed a colloidal synthesis of semiconductor nanostructures with a different topology, such as a ring (g = 1) and a double ring (g = 2). Semiconductor quantum rings (Figure 2) are of great fundamental interest because their non-trivial topology creates novel physical properties. At the same time, toroidal topology is difficult to achieve for colloidal nanocrystals and epitaxially grown semiconductor nanostructures. We developed the synthesis of luminescent colloidal CdSe nanorings and nanostructures with double and triple toroidal topology. The nanorings form during controlled etching and rearrangement of two-dimensional nanoplatelets. We discuss possible mechanism of the transformation of nanoplatelets into nanorings and potential utility of colloidal nanorings for magneto-optical (e.g., Aharonov–Bohm effect) and other applications.

16.Synthesis of new forms of CdSe: atomically-defined molecular wires, gels, and ordered mesoporous assemblies

Related publication acknowledging AFOSR support:
Hudson, M. H.; Dolzhnikov, D. S.; Filatov, A. S.; Janke, E. M.; Jang, J.; Lee, B.; Sun, C.; Talapin, D. V. J. Am. Chem. Soc. 2017, 139, 3368-3377.

We investigated the structure and properties of soluble chalcogenidocadmates, a molecular form of cadmium chalcogenides with unprecedented one-dimensional bonding motifs. The single crystal x-ray structure reveals that sodium selenocadmate consists of infinite one-dimensional wires of $(Cd_2Se_3)_n^{2n-}$ charge balanced by Na^+ and stabilized by coordinating solvent molecules. Exchanging the sodium cation with tetraethylammonium or

didodecyldimethylammonium expands the versatility of selenocadmate by improving its solubility in a variety of polar and nonpolar solvents without changing the anion structure and properties. The introduction of a micelle-forming cationic surfactant allows for the templating of selenocadmate, or the analogous telluride species, to create ordered organic-inorganic hybrid CdSe or CdTe mesostructures. Finally, the interaction of selenocadmate "wires" with Cd^{2+} ions creates an unprecedented gel-like form of stoichiometric CdSe. We also demonstrate that these low-dimensional CdSe species show characteristic semiconductor behavior, and can be used in photodetectors and field-effect transistors.

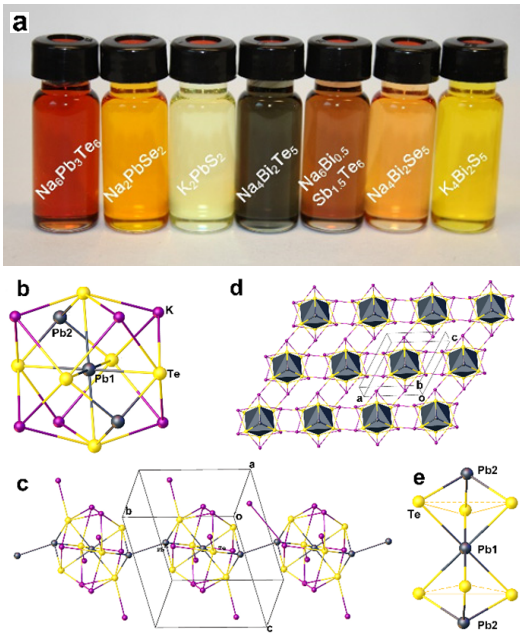


17. Atomically precise soluble lead and bismuth chalcogenidometallates and their use as solders for thermoelectric materials

Related publication acknowledging AFOSR support:
Zhang, H.; Son, J. S.; Dolzhnikov, D. S.; Filatov, A. S.; Hazarika, A.; Wang, Y.; Hudson, M. H.; Sun, C.-J.; Chattopadhyay, S.; Talapin, D. V. Chem. Mater. 2017, 29, 6396-6404.

We developed the syntheses of largely unexplored lead- and bismuth chalcogenidometallates in solution phase (Subfigure a). Using N_2H_4 as the solvent, new compounds such as $K_6Pb_3Te_6{\cdot}7N_2H_4$ were obtained (Subfigure b-e). These soluble molecular compounds underwent cation exchange processes using resin chemistry, replacing Na^+ or K^+ by decomposable $N_2H_5^+$ or tetraethylammonium cations. They also transformed into stoichiometric lead- and bismuth chalcogenide nanomaterials with the addition of metal salts. Such a versatile chemistry led to a variety of composition-matched solders to join lead- and bismuth chalcogenides and tune their charge transport properties at the grain boundaries. Solution-processed thin films composed of $Bi_{0.5}Sb_{1.5}Te_3$ micro-particles soldered by $(N_2H_5)_6Bi_{0.5}Sb_{1.5}Te_6$ exhibited thermoelectric power factors (~28 μW/cm K2) comparable to those in vacuum-deposited $Bi_{0.5}Sb_{1.5}Te_3$ films. The soldering effect can also be integrated with attractive fabrication techniques for thermoelectric

modules, such as screen-printing, suggesting the potential of these solders in the rational design of printable and moldable thermoelectrics.



Patent Application Filed:

Optical Resonance Imaging (G.S. Engel & M.A. Allodi)

Publications:

1. Forgy, C. C. & Mazziotti, D. A. Relations between Environmental Noise and Electronic Coupling for Optimal Exciton Transfer in One- and Two-Dimensional Homogeneous and Inhomogeneous Quantum Systems. *J Chem Phys* **141,** 224111, (2014).

2 Baghani, E., O'Leary, S. K., Fedin, I., Talapin, D. V. & Pelton, M. Auger-Limited Carrier Recombination and Relaxation in Cdse Colloidal Quantum Wells. *J Phys Chem Lett* **6,** 1032-1036, (2015).

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Abstract

Nanomaterials are defined by their shape, size, material, structure, and they offer the opportunity to tailor materials properties in ways that are distinctly different from the bulk materials from which they are derived. However, to make practical materials with novel functionality, these materials must be joined in a way that preserves these novel properties while combining them with others from dissimilar materials. The goal of this project was to develop, measure, and model motifs to couple these nanocrystalline materials and thereby unlock the combinatorial complexity of this chemical space. In this regard, it is our vision that these "designer atoms" will permits materials with complexity and variation that will far surpass traditional materials, but only if we understand how to link the nanoparticles together such that electronic motion among the particles becomes correlated just as electrons in simple molecules are correlated. Unlike discrete atoms, however, nanoparticles are continuously variable. The possibilities are limitless.
Our project has combined inorganic synthesis of linked nanoparticles, ultrafast spectroscopy of coherent coupling, and theoretical calculations of long-range electronic correlation to create and to optimize linkages between nanocrystal "building blocks" to permit construction of new materials.

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New discoveries, inventions, or patent disclosures:

Do you have any discoveries, inventions, or patent disclosures to report for this period?

Yes

Please describe and include any notable dates

We filed a patent application for Optical Resonance Imaging in November of 2017.

Do you plan to pursue a claim for personal or organizational intellectual property?

Yes

Changes in research objectives (if any):

Change in AFOSR Program Officer, if any:

Extensions granted or milestones slipped, if any:

NCE granted through 3/31/2018

AFOSR LRIR Number

LRIR Title

Reporting Period

Laboratory Task Manager

Program Officer

Research Objectives

Technical Summary

Funding Summary by Cost Category (by FY, $K)

	Starting FY	FY+1	FY+2
Salary			
Equipment/Facilities			
Supplies			
Total			

Report Document

Report Document - Text Analysis

Report Document - Text Analysis

Appendix Documents

2. Thank You

E-mail user

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