様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９　（共通）

科学研究費助成事業　　研究成果報告書

令和　６ 年　 ６ 月 １３ 日現在

機関番号：１２６０５
研究種目：基盤研究(C)（一般）
研究期間：2021～2023
課題番号：２１Ｋ０４８１５

研究課題名（和文）High Performance Supercapacitors based on Hierarchical Colloidal Quantum Dot Assemblies

研究課題名（英文）High Performance Supercapacitors based on Hierarchical Colloidal Quantum Dot Assemblies

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交付決定額（研究期間全体）：（直接経費）　　3,100,000円

研究成果の概要（和文）：当研究は、高性能スーパーキャパシタの構成要素として、コロイド量子ドット(CQD)材料集合体を利用する可能性を示すものである。QDの精密な組み立て工学により、階層的ナノ多孔質薄膜の形成を確立、精査できる。こうしたQDの階層的ナノ細孔をスーパーキャパシタ電極として使用することで、現在の最先端スーパーキャパシタ材料に匹敵する高性能エネルギー貯蔵能力が実証される。多種類のQD集合体における電荷輸送の包括的な研究を行い、この種の材料を用いたスーパーキャパシタの性能をより向上させる手がかりを得た。他の金属硫化物の合成と計算科学研究により、新たに環境に優しく、豊富かつ軽量なQD化合物の調査探索の道も拓いた。

研究成果の学術的意義や社会的意義
本研究は、コロイド状量子ドット(QD)をスーパーキャパシタの構成要素として用いることで、高い出力密度とエネルギー密度を大幅に実現できることを示している。この研究成果は、電化によるゼロ・カーボン社会の実現に不可欠な主要エネルギー貯蔵デバイスの1つである高性能スーパーキャパシタの将来的な開発の基礎を築くものである。学術的には、この概念実証研究は、他の多くのQD化合物のさらなる探求を刺激し、エネルギー貯蔵材料としての潜在的利用を最大化するためにそれらの集合体を制御する。また、量子閉じ込め系を利用したエネルギー貯蔵材料としての可能性を探る第一歩でもある。

研究成果の概要（英文）：This research project demonstrates the prospects of utilizing assemblies of colloidal quantum dot (QD) materials as the building blocks of high-performance supercapacitor devices. Through precise assembly engineering of the colloidal QDs, the formation of hierarchical nanoporous thin film can be established and scrutinized. The use of these QD hierarchical nanopores as micro-supercapacitor electrodes demonstrates high performance energy storage capabilities comparable to the current state-of-the-art supercapacitor materials. Within this project, comprehensive investigations of the charge carrier transport in various kinds of colloidal QD assemblies were performed, providing clues to further enhance the performance of supercapacitor devices based on this class of this materials. Furthermore, the search of new, environmentally-friendly, abundant, and lighter colloidal QD compounds is also pioneered by computational studies and the synthesis of the other metal-chalcogenide nanocrystals.

研究分野：ナノ材料科学関連、応用物理

キーワード：colloidal quantum dots　supercapacitors　nanopores　energy devices　electric double layer　nanocrystals　hierarchical assemblies　electronic transport

様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９（共通）

１．研究開始当初の背景

High energy density, high power density, long cycling life, cost-effectiveness, and environmental safety are pivotal parameters in developing advanced energy storage devices. These characteristics are crucial to addressing various applications' growing energy demands and sustainability concerns. Electrochemical-based energy storage devices, particularly electrochemical supercapacitors, are at the forefront of scientific and technological development. These devices occupy a unique position between conventional capacitors and batteries, offering higher energy density than traditional capacitors, greater power density than batteries (exceeding 1 W/kg), and an extended lifecycle. Their promise as energy storage devices is especially significant for electronic systems requiring high power density, high energy density, durability, and rapid charging and discharging capabilities, such as electric vehicles, memory backup systems, and wearable electronics. Moreover, electrochemical supercapacitors can efficiently store electrical energy harvested from intermittent renewable sources like wind and solar power, delivering it quickly when needed. Enhancing the energy density of supercapacitors beyond the current state-of-the-art is a critical research goal to maximize their potential.

The research motivation for advancing supercapacitor technology heavily emphasizes nanostructuring electrode materials and their functionalization and optimizing the combination of electrodes and electrolytes. Historically, efforts to develop supercapacitor electrodes using nanostructured materials have focused primarily on increasing the surface area, as capacitance is directly proportional. However, this approach faces limitations concerning the minimum size of nanostructures and the effective penetration of electrolyte molecules to access the surface of these nanostructures. Consequently, EDLCs have generally exhibited lower energy density than pseudo-capacitors due to limited specific surface area and compatibility between the electrode and electrolyte. Common electrode materials for EDLCs include porous carbon and various carbon allotropes, such as nanotubes and graphene, which possess large specific surface areas.

As nanomaterials, colloidal QD (CQD) solids offer flexibility and low cost through solution processing and unique zero-dimensional (0-D) size-dependent properties. The small size of individual QDs gives rise to the quantum confinement effect of the carrier wavefunction, which is the size dependency of electronic band gaps and the formation of discrete energy levels. This quantum confinement effect becomes significant when nanoparticles (NPs) are smaller than their electron Bohr radius, typically much smaller than 10 nm. For instance, the Bohr radius for lead sulfide (PbS), used as a model material in this context, is approximately 20 nm. The smaller the size relative to this parameter, the stronger the quantum confinement effect. Thus far, supercapacitor electrodes utilizing NPs and their assemblies generally consist of NPs with sizes ranging from tens to hundreds of nanometers. This size range does not permit the full exploitation of quantum capacitance in supercapacitors.

The research motivation behind this project focuses on overcoming the limitations of current nanostructuring techniques to increase specific surface areas and achieve better compatibility between electrodes and electrolytes. Emphasizing the development and integration of advanced nanomaterials, such as CQD solids, can significantly leverage their quantum confinement properties to improve energy density and overall performance. Such advancements are critical for meeting the growing demands for high-performance energy storage solutions in various applications. The successful realization of these goals will contribute to the broader effort to create sustainable, efficient, and high-capacity energy storage systems.

２．研究の目的

The project aims to develop a high-performance supercapacitor (Fig.1) based on hierarchical assemblies of solution-processable CQDs to demonstrate high energy and high-power density values. The large surface-area-to-volume ratio of QD assemblies enables us to obtain significantly large capacitance in EDLCs. This research will lay the groundwork for further exploitation of CQDs and nanocrystal (NC) materials as the building block of supercapacitor devices in which the quantum capacitance effect of the QDs can enhance the capacity of the much-needed energy storage devices. This project focuses on utilizing CQDs with diameters less than their electron Bohr radius. For the model system of lead sulfide (PbS), we use QDs with 4 ~ 12 nm diameters.

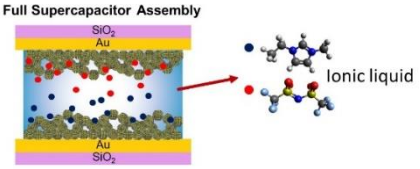

Fig. 1. Schematic of an electric double layer supercapacitor device utilizing CQD assemblies

３．研究の方法

A. Assembly control

The first step of this research project is to control the formation of colloidal quantum dot (CQD) assemblies to create well-ordered superlattices and hierarchical porous structures for supercapacitor electrodes. Two primary methods are utilized: assembly at the liquid/air interface and the layer-by-layer (LbL) dip-coating process. The liquid/air interface assembly forms well-ordered superlattices by combining this technique with precise ligand stripping processes targeting specific crystalline facets of rock-salt PbS QDs. Proper ligand-stripping agents are essential for this method, and multiple ligand-stripping and exchange steps can be applied (*Nanoscale*, 11, 20467, 2019).

The LbL dip-coating process is used to form hierarchical nanoporous structures with CQDs. Each layer undergoes a ligand exchange process to reduce interdot distance and enhance electronic couplings among

the QDs. (*NPG Asia Mater.,* 12, 33, 2020). Optimization of this process involves varying dipping and retraction speed, angle during deposition, and dissolving solvents to create the hierarchical porous structure on metallic substrates. Different short ligand variations are optimized to couple the CQDs while forming the porous assemblies electronically. Also, halide ions like iodide passivate the remaining dangling bonds on the CQDs' surface, reducing electron traps that could affect the performance of the charge accumulation device. Different sources of iodide with various counterions are tested to find the optimal trap passivation recipe. Comprehensive morphological characterizations of the assemblies are performed using electron microscopy (TEM and SEM), synchrotron-based x-ray scattering (GISAXS/GIWAXS), and atomic force microscopy (AFM).

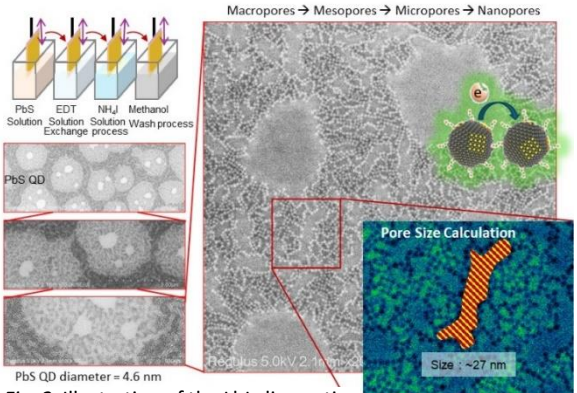

Fig. 2. Illustration of the LbL dip coating process and the FE-SEM images of the PbS QD hierarchical nanopores.

B. Electronic properties investigation

To perform electronic properties investigations, the main focus was to elucidate the electron transport properties of the CQD assemblies using EDL transistors (EDLT). To form the EDLT of the QD solids, the PbS CQDs were deposited using the abovementioned process on SiO_2/Si substrates with pre-patterned electrodes for measurements. In the case of the QDSLs prepared using the liquid/air interface method, Langmuir-Schaffer film transfers onto the pre-patterned substrate were performed. To make the hierarchical nanopores assemblies, the QDs were directly deposited by LbL dip coating onto the pre-patterned substrates.

All the EDLT transistor measurements were performed inside the N_2 glovebox to ensure that the behavior of the devices is intrinsic. It has been known that oxygen and moisture exposure to PbS QD can significantly alter their electron transport properties. Low-temperature transport measurements were performed using a 4K close-loop GM cryostat directly connected to the N_2 glovebox. Through EDLT measurements and the complementary FET measurements, the charge carrier mobility information in the QD superlattices can be obtained. Furthermore, the close similarity in terms of working principles between EDLT and EDLC allowed the determination of the charge accumulation capability prospects of the QD assemblies. This similarity also includes the possibility of filling the discrete energy levels of the QDs. To confirm electronic states band filling, spectroelectrochemistry measurements were also performed by combining a UV-Vis-NIR spectrophotometer and an electronic unit. Field-induced doping would occur in the QD assemblies by applying voltage on the EDL gate. Upon filling the discrete energy levels, the bleaching of the excitonic peak in the absorption spectra should be observed. From this measurement, we should be able to quantify the number of accumulated electrons in the discrete energy levels of the QDs.

C. Fabrication and measurements of QDHN Supercapacitor Electrodes and Devices

In order to prepare the electrodes for the supercapacitor devices, the hierarchical nanoporous assembly of the colloidal QDs was deposited using LbL dip coating on Au-coated SiO_2/Si substrates that act as the current collector. The numbers of deposited QD layers varied. Furthermore, the QDHN variations were only crosslinked by 1,2-ethanedithiol, and those were also treated with iodide.

Three-electrodes electrochemistry measurements were performed to validate the functionality of the QDHN-based electrodes as capacitive electrodes. A complete suite of cyclic voltammetry and galvanostatic charge-discharge measurements were performed. Varying of ionic liquids to find the best combination was performed at this stage. If handled properly, PbS CQDs are ambipolar materials, enabling charge transport of holes and electrons and accumulating those two. Therefore, to build the full supercapacitor devices, two nearly identical QDHN electrodes were used to form symmetric geometry, sandwiching an ionic liquid layer. These full supercapacitor devices were subjected to cyclic voltammetry measurement and multiple cycles of galvanostatic charge-discharge (GCD) measurements. Besides obtaining the precise power density and energy density stored in the supercapacitor devices, multiple-cycle GCD measurements were also essential to test the performance stability of the devices over thousands of charging and discharging cycles. At the end of the project, a plan to mix the QDHN with carbon nanotubes as a medium with higher electronic conductivity was raised. Preliminarily, EDLC devices utilizing networks of polymer-wrapped carbon nanotubes were developed to anticipate the possibility of this mixing.

D. Computational study for material design

Although the investigation of the electronic properties and the supercapacitor devices of PbS CQDs are this study's main objects, prospecting other possible CQD compounds that can replace PbS compounds is also the goal of this project through computational studies and (in the next step) synthetic process.

Other metal-sulfide compounds were prospected as the alternative to PbS. One of them is iron-sulfide families. Iron, having many variations of oxidation numbers, may lead to many variations of sulfide compounds. While pyrite (FeS_2) is well-known, many other compounds have been investigated less, including the h-FeS (Fe_7S_8) phase. DFT-based computational studies were performed to predict the electronic properties of these compounds by collaborating with an international partner. It is not only the band structure of

the compounds that was calculated but also the formation energy that may provide clues for the synthesis efforts, as well as several other relevant points that are essential to be investigated for supercapacitor material designs. The influence of the defect formations and the subsequent metal doping into these compounds were also simulated. Significantly, their influence on the change in the electronic density of states and the subsequent implications for exploiting the formed associated quantum capacitance for supercapacitor device applications were thoroughly simulated.

E. Synthesis of new Colloidal QD compounds

Two new metal chalcogenide CQD compound classes were pioneered: Tin-based (Sn-based) and Iron-based (Fe-based). The initial approach involved the well-established hot-injection method, commonly used for Pb-, Hg-, and Cd-chalcogenides. However, this method proved challenging for Sn-based and Fe-based CQDs, prompting the exploration of alternative methods. Sensitive to synthesis conditions, the CQDs were synthesized inside an inert N_2 glovebox, including precursor preparations. Variations of molecular ligands were used to facilitate easier complexation and solubilization of the metal precursors, along with optimized sulfur precursors. Controlling the size and dispersity of the produced nanocrystals (NCs) is critical, achieved by precisely tuning the synthesis-temperature, -duration, and abruptly stopping the reaction by reducing the reactor temperature. Introducing a cold solvent to immediately decrease the temperature was promoted over external cooling methods. This abrupt cooling strongly affects the size distribution of the NCs, determining their optical and electronic properties. The cold solvent and its amount were optimized to achieve a balance in reaction kinetics and thermodynamics, obtaining the desired NCs.

The NCs were characterized using X-ray diffraction to determine crystallography and transmission electron microscopy. UV-Vis-NIR spectrophotometry and diffuse reflectance measurements identified the optical bandgap of the NCs. Simple photoconductivity measurements and initial attempts to fabricate supercapacitor electrodes were performed to demonstrate the potential of these new NCs. These efforts resulted in protocols to synthesize Sn-based and Fe-based CQDs with controlled properties, showing promise for supercapacitor applications through enhanced electronic and optical characteristics.

４．研究成果

A. QD Assembly Control and Electronic Properties

We demonstrated significant findings for the fundamental electronic properties of CQD superlattices, revealing their potential for energy storage devices. The electronic transport and charge accumulation in PbS QD assemblies were examined, focusing on structural arrangements and doping mechanisms. We discovered the importance of QD superstructures in enhancing electronic properties through controlled assembly and precise field-induced doping techniques. Field-induced doping in different PbS QD assemblies by an EDL gating was investigated using spectroelectrochemistry measurements. Monolayers of PbS QD assemblies, prepared as square superlattices or ligand-exchanged assemblies, were deposited on pre-patterned transparent substrates. These assemblies exhibited an excitonic peak in their near-IR absorption spectra without gating. The electric-double layer gating shifts the Fermi level energy, allowing access to the discrete energy levels of the QDs. The excitonic peak was bleached upon filling, quantifying the number of electrons filling the discrete energy levels. [***Nanoscale*** 13, 14001 (2021)].

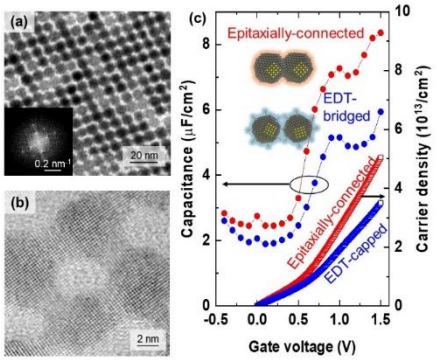

Fig. 3. (a) TEM of QD superlattice containing 8.1 nm PbS QDs. (b) HR-TEM showing the epitaxial connection of this superlattice. (c) The comparison of gate voltage dependent capacitance values of the EDLTs of epiQDSL and EDT-bridged QD assembly, and the corresponding accumulated sheet electron density.

We explored the formation of epitaxially connected PbS QD superlattices (QD-SLs) (Fig. 3a) and their transition from insulating to metallic states upon high carrier density doping. We used an EDL transistor (EDLT) to achieve high carrier densities, surpassing the critical doping concentration needed for the insulator-to-metal transition (IMT). The epitaxially-connected QD-SLs exhibited temperature-independent conductivity at high carrier densities, indicating metallic behavior. This study underscores the importance of epitaxial connections and orientational order in achieving delocalized electron transport in QD assemblies [***Nature Comm.*** 14, 2670 (2023)]. These results demonstrated the potential of highly ordered superlattices and provided valuable insights for different QD assemblies. The EDLT method allows for high carrier density accumulation, essential for observing band-filling, crucial for enhancing supercapacitor devices of nanomaterials. Charge carrier accumulation in these studies is achieved through ionic gating, providing continuous and reversible doping (Fig. 3b). This method is effective in both PbS square assembly and epi QDSLs, enabling the exploration of electronic transport mechanisms at high carrier densities.

B. High-Performance Supercapacitor Devices

We demonstrated the advantageous properties of QDs, particularly their high surface-to-volume ratio, which is critical for enhancing supercapacitor performance. Addressing the challenge of achieving a structure that maintains high electrical conductivity and efficient ion diffusion, we constructed additive-free ultrahigh energy density EDLCs using PbS QDs assembled into hierarchical nanoporous structures, leading

to high-performance devices. The fabrication process of these supercapacitor electrodes involves a meticulous layer-by-layer (LbL) dip-coating method combined with ligand exchange to create the QD hierarchical nanopore (QDHN) structure. This approach ensures optimal spacing of the QDs to balance high conductivity with ion accessibility (Fig. 4a-b). Using ionic liquid as the electrolyte, the electrodes demonstrate impressive performance metrics, including a volumetric energy density of 95.6 mWh cm^{-3} and a power density of 13.5 W cm^{-3}. The hierarchical nanoporous structure facilitates efficient ion interaction and charge mobility, both critical for high-performance supercapacitors. The electrochemical performance of the QDHN electrodes is thoroughly examined, highlighting their superior capacitance and rate capability compared to other supercapacitor materials. Iodide-treated QDHN electrodes show enhanced ion diffusion and charge transport, significantly contributing to their high performance (Fig. 4c). These electrodes achieve a volumetric capacitance of 366 F cm^{-3}, among the highest for state-of-the-art supercapacitor materials, without additional conductive agents [***ACS Appl. Mater. & Interfaces*** 16, 24889 (2024)].

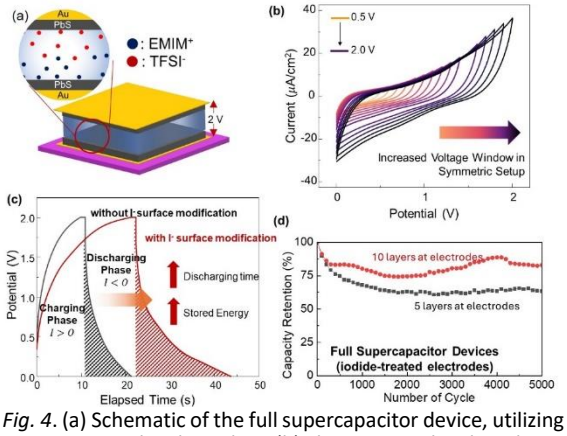

Fig. 4. (a) Schematic of the full supercapacitor device, utilizing EMIM-TFSI as the electrolyte. (b) The measured cyclic voltammetry plots showing the stable operational potential window of the complete supercapacitor. (c) Galvanostatic charge discharge (GCD) characteristics of the supercapacitors with their QDHN electrodes treated or untreated with iodide ligands. (d) Cycling performance of the QDHN-based supercapacitor devices with different numbers of iodide-treated layers of electrodes showing stable capacity retention.

Further investigation into the charge storage mechanism reveals a mix of diffusion-controlled and surface-capacitive-controlled processes in the QDHN electrodes. The iodide treatment enhances the porosity and conductivity of the QDHN structures and supports consistent performance across different thicknesses of the electrode layers. The developed supercapacitor devices were stable over 1000 cycles with good capacitance retention (Fig. 4d). This finding demonstrates the potential for scalable production of QDHN-based supercapacitors, maintaining high-performance metrics even as the electrode thickness increases. The innovative QDHN architecture offers significant advantages for rapid ionic transport and charge accumulation, paving the way for further advancements in high-performance energy storage devices. Future research directions include exploring superior electrolytes, more robust QD compounds, and scaling production processes to accelerate the development of these promising supercapacitors.

C. Towards New QD Material Discovery for Future Supercapacitor Devices

We embarked on both computational studies and synthesis experiments to find alternative QD compounds to potentially replace PbS QDs. Although carbon dots as potential alternatives [***RSC Adv.***, 11, 39917 (2021)], challenges related to their quantum confinement properties and end-of-life issues led us to focus on alternative metal chalcogenides.

The computational studies focused on hexagonal iron sulfide (h-FeS, or Fe_7S_8). It is known for its non-centrosymmetric structure and antiferromagnetic configuration. Through DFT calculations, we investigated the role of intrinsic point defects on this compound's electronic structure [***J. Phys. Chem. Lett.*** 12, 10777 (2021)]. Starting from defect considerations, which are likely in a QD system characterized by many surface defects, we found that iron vacancies can induce midgap states significantly affecting the electronic properties, such as bandgap narrowing and enhanced conductivity. The formation of these defects under different synthesis conditions (S-rich vs S-poor) and their impact on the electronic structure were thoroughly analyzed. By delving into defect engineering, we identified key strategies to develop this material for supercapacitor [***Electrochim. Acta***, 449, 142235 (2023)]. We predicted that p-type defects would be important in the h-FeS structure to enhance capacitance through quantum capacitance mechanisms. DFT calculations of Cr-doped h-FeS anodes showed much higher quantum capacitance, than pristine h-FeS.

Experimentally, a new method for synthesizing CQDs was developed, allowing for synthesizing new, challenging compounds. This method led to the discovery of colloidal NCs of π-SnS (tin sulfide) [***J. Phys. Chem. C*** 126, 5323 (2022)] (Fig. 5a). Tin, being more environmentally friendly, abundant, and lighter than lead, offers significant advantages. The new QD NC compound was comprehensively characterized, and size-dependent bandgap values confirmed that these NCs act as QDs (Fig. 5b-c). Photodetector devices developed with these QDs demonstrated conduction channel paths performing on par with early PbS QDs. The use of this new compound for supercapacitor electrodes is still being pioneered beyond the scope of this current project. On the other hand, a similar synthesis method is now being exploited as a virtue to synthesize the other tin-chalcogenide NCs and the iron-sulfide NCs.

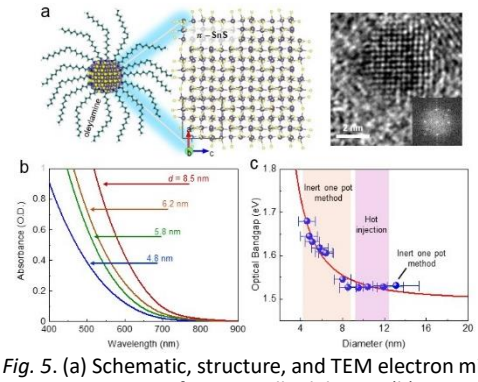

Fig. 5. (a) Schematic, structure, and TEM electron microscopy images of π-SnS colloidal NCs. (b) Optical absorption spectra of the inert one-pot synthesized π-SnS NC solutions with variations of NC diameters. (c) Plot of the size-dependent optical bandgaps of the π-SnS NC indicating quantum confinement effect.

５．主な発表論文等

〔雑誌論文〕　計8件（うち査読付論文　8件／うち国際共著　8件／うちオープンアクセス　2件）

１．著者名 Irham Muhammad Alief、Septianto Ricky Dwi、Wulandari Retno Dwi、Majima Yutaka、Iskandar Ferry、Iwasa Yoshihiro、Bisri Satria Zulkarnaen	４．巻 16
２．論文標題 High Volumetric Energy Density Supercapacitor of Additive-Free Quantum Dot Hierarchical Nanopore Structure	５．発行年 2024年
３．雑誌名 ACS Applied Materials & Interfaces	６．最初と最後の頁 acsami.4c02517
掲載論文のDOI（デジタルオブジェクト識別子） 10.1021/acsami.4c02517	査読の有無 有
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１．著者名 Shibata Kenji、Yoshida Masaki、Hirakawa Kazuhiko、Otsuka Tomohiro、Bisri Satria Zulkarnaen、Iwasa Yoshihiro	４．巻 14
２．論文標題 Single PbS colloidal quantum dot transistors	５．発行年 2023年
３．雑誌名 Nature Communications	６．最初と最後の頁 7486
掲載論文のDOI（デジタルオブジェクト識別子） 10.1038/s41467-023-43343-7	査読の有無 有
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１．著者名 Septianto Ricky Dwi、Miranti Retno、Kikitsu Tomoka、Hikima Takaaki、Hashizume Daisuke、Matsushita Nobuhiro、Iwasa Yoshihiro、Bisri Satria Zulkarnaen	４．巻 14
２．論文標題 Enabling metallic behaviour in two-dimensional superlattice of semiconductor colloidal quantum dots	５．発行年 2023年
３．雑誌名 Nature Communications	６．最初と最後の頁 2670
掲載論文のDOI（デジタルオブジェクト識別子） 10.1038/s41467-023-38216-y	査読の有無 有
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１．著者名 Irham Muhammad Alief、Muttaqien Fahdzi、Bisri Satria Zulkarnaen、Iskandar Ferry	４．巻 449
２．論文標題 Enhancing quantum capacitance of iron sulfide supercapacitor through defect-engineering: A first-principles calculation	５．発行年 2023年
３．雑誌名 Electrochimica Acta	６．最初と最後の頁 142235～142235
掲載論文のDOI（デジタルオブジェクト識別子） 10.1016/j.electacta.2023.142235	査読の有無 有
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1．著者名 Miranti Retno、Septianto Ricky Dwi、Kikitsu Tomoka、Hashizume Daisuke、Matsushita Nobuhiro、Iwasa Yoshihiro、Bisri Satria Zulkarnaen	4．巻 126
2．論文標題 π-SnS Colloidal Nanocrystals with Size-Dependent Band Gaps	5．発行年 2022年
3．雑誌名 The Journal of Physical Chemistry C	6．最初と最後の頁 5323～5332
掲載論文のDOI（デジタルオブジェクト識別子） 10.1021/acs.jpcc.2c00266	査読の有無 有
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1．著者名 Irham Muhammad Alief、Muttaqien Fahdzi、Bisri Satria Zulkarnaen、Iskandar Ferry	4．巻 12
2．論文標題 Role of Intrinsic Points Defects on the Electronic Structure of Metal-Insulator Transition h-FeS	5．発行年 2021年
3．雑誌名 The Journal of Physical Chemistry Letters	6．最初と最後の頁 10777～10782
掲載論文のDOI（デジタルオブジェクト識別子） 10.1021/acs.jpclett.1c02360	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

1．著者名 Permatasari Fitri Aulia、Nakul Fitriyanti、Mayangsari Tirta Rona、Aimon Akfiny Hasdi、Nuryadin Bebeh Wahid、Bisri Satria Zulkarnaen、Ogi Takashi、Iskandar Ferry	4．巻 11
2．論文標題 Solid-state nitrogen-doped carbon nanoparticles with tunable emission prepared by a microwave-assisted method	5．発行年 2021年
3．雑誌名 RSC Advances	6．最初と最後の頁 39917～39923
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1．著者名 Liu Liming、Septianto Ricky Dwi、Bisri Satria Zulkarnaen、Ishida Yasuhiro、Aida Takuzo、Iwasa Yoshihiro	4．巻 13
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Satria Zulkarnaen Bisri

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10th International Conference of sensors and 4th International Conference on Advanced Materials and Practical Nanotechnology (AsiaSense2023) - Bali Indonesia（招待講演）（国際学会）

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1．発表者名
Satria Zulkarnaen Bisri

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3．学会等名
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4．発表年
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Satria Zulkarnaen Bisri, Ricky Dwi Septianto, Retno Miranti, Tomoka Kikitsu, Takaaki Hikima, Daisuke Hashizume, Nobuhiro Matsushita, Yoshihiro Iwasa

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〔図書〕　計0件

〔産業財産権〕

〔その他〕

東京農工大学 工学研究院　BISRI研究室 https://www.sustainable-quantum-nanomaterials-devices.com/

6．研究組織

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研究協力者	セプティアント　リッキー・ドゥウィ (Septianto Ricky Dwi)		
研究協力者	ミランティ　レトノ (Miranti Retno)		
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研究協力者	引間　孝明 (Hikima Takaaki)		
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7．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

8．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関

インドネシア	Institut Teknologi Bandung			
インドネシア	Institut Teknologi Bandung			
オーストリア	IST Austria			
スイス	ETH Zurich			
インドネシア	Institut Teknologi Bandung	Universitas Pertamina		
オーストリア	IST Austria			
スイス	ETH Zurich			