

Functional Materials Science and Engineering Research Section

Y. Miyauchi, Professor

1. Introduction

Our research section focuses on the physical properties, functions, and energy applications of quantum materials that exhibit significant quantum mechanical effects, such as carbon nanotubes, two-dimensional semiconductors, and recently discovered topological materials. The aim is to create new technologies for highly efficient use of solar light/thermal energy that will contribute to the realization of a sustainable energy society. To understand the unique physical properties of these materials from the fundamental principles and extract superior functions that exceed the limits of conventional materials, we are promoting interdisciplinary research that covers basic sciences, including materials synthesis and condensed matter physics, as well as thermal, mechanical, electronic, and optical engineering along with the fabrication of integrated nanomaterials. Following are the main research achievements in the year of 2025.

2. Thermal and nonthermal exciton light emissions from carbon nanotubes above 1000 K

High-temperature light emission from nanomaterials has been extensively studied for light-emitting device applications. However, thermodynamic properties of their light emission under high-temperature conditions, which are critical for energy applications, have not been fully elucidated. In this study, we demonstrated that carbon nanotubes (CNTs) emit nonthermal light, specifically exciton luminescence in the near-infrared (NIR) region, even at very high temperatures [1]. By investigating the chemical potential of photons, which indicates the extent of nonthermal excitation beyond thermal equilibrium, we showed that exciton light emission from a semiconducting nanotube maintains a nonthermal condition above 1000 K, enabling intense radiation that exceeds thermal radiation at the same temperature. Furthermore, the chemical potential of photons emitted by an individual metallic nanotube under electric-current injection far surpasses that of semiconducting nanotubes at ≈ 1000 K. These findings facilitate applications of CNTs as high-intensity, narrow-band NIR emitters operable even at very high temperatures for advanced energy-conversion devices.

3. Robust exciton binding energy in aggregated structure-sorted carbon nanotubes revealed by two-photon excitation spectroscopy

CNTs exhibit sharp excitonic resonances in their

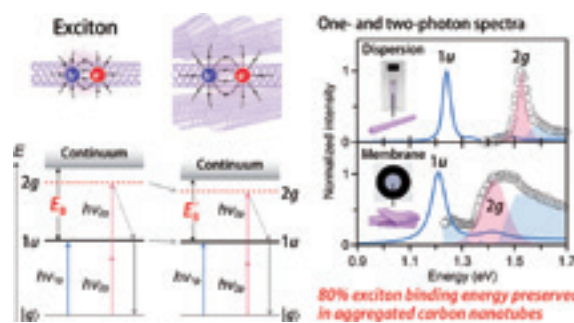


Fig. 1. Schematic of exciton Rydberg series in isolated and aggregated CNTs (left) and observation of exciton Rydberg series in these CNTs to determine exciton binding energies using two-photon excitation photoluminescence spectroscopy (right).

near-infrared optical spectra even when aggregated in macroscale assemblies. This characteristic offers promising opportunities for utilizing CNT assemblies as excitonic optofunctional materials. However, as a crucial factor determining the dominance of excitonic resonance, exciton binding energy in high-purity structure-sorted CNT membranes has remained to be clarified. In this study, we clarified modifications to the exciton binding energy in high-purity, structure-sorted semiconducting CNTs due to aggregation [2]. We prepared membranes consisting of aggregated CNTs with high single chiral structure purity. Using one- and two-photon spectroscopies, we observed the shrinkage in the energy spacing of the exciton Rydberg series in aggregated CNTs (Fig. 1). By comparison of the experimental results with theoretical calculations, the exciton binding energy of the aggregated CNT membrane was deduced to be about 0.26 eV, maintaining approximately 80% of the value in the isolated CNTs stabilized by wrapping with organic polymers in toluene. We further confirmed that the results are consistent with the infrared dielectric constant separately determined from mid-infrared optical measurements. These findings show promising prospects for utilizing exciton resonances in CNT aggregations not only at low temperatures but also at high temperatures.

4. Carbon-nanotube-based all-dielectric near-infrared perfect absorbers

Achieving sharp and strong near-infrared (NIR) absorption of thin films is important for various optical

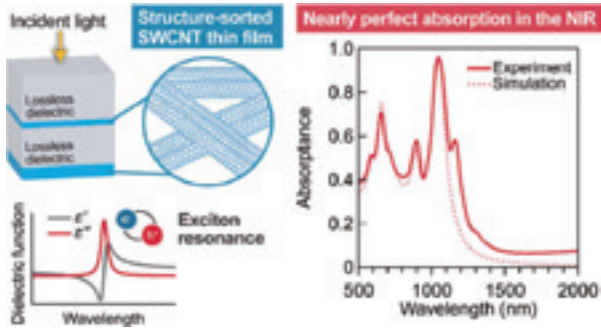


Fig. 2. Structure of CNT-based all-dielectric NIR perfect absorber (left) and its absorptance spectra (right).

devices including wavelength selective emitters in thermophotovoltaic energy conversion devices. In this study, we demonstrated design and fabrication of an all-dielectric NIR absorber with nearly unity absorptance based on the strong exciton resonance of structure-sorted semiconducting CNT ultrathin films [3,4]. Previous studies of perfect absorbers have mainly focused on fine-structured designs, such as photonic crystals and metasurfaces. However, these designs face scalability and thermal stability challenges. We designed and fabricated CNT-based all-dielectric NIR near-perfect absorbers with a simple planar layered structure (Fig. 2). This design was inspired by the Salisbury screen typically used for electromagnetic waves at considerably longer wavelengths. Beyond the conventional Salisbury screen structure, all-dielectric planar absorber design in the NIR can be achieved owing to both high absorption and reflection of the CNT thin films due to the distinct exciton resonance. The theoretical and experimental results showed nearly perfect absorption at the first exciton resonance wavelength of structure-sorted CNTs in the planar four-layer structure. The proposed absorber structure offers resonant wavelength tunability simply by selecting the structure of CNTs, robustness against unexpected variations in film thicknesses during fabrication processes, and potential for scalability and thermal stability. This study highlights the potential applications of the proposed absorber in several areas such as sensing, photodetection, and energy conversion.

5. Broadband solar selective absorber with Dallenbach-type bilayer structure achieved using carbon nanotube membranes with tailored optical spectra

Spectrally selective absorbers that maximize solar absorption and minimize thermal radiation loss are crucial for efficient solar thermal energy harvesting. However, limitations imposed by the intrinsic properties of conventional materials hinder the fabrication of interference-based absorbers with desired optical properties. In this study, we developed a high-performance solar absorber with a Dallenbach-type

dielectric–metal tandem structure using an ultrathin, sub-quarter-wavelength thickness CNT membrane with tailored optical spectra as the absorbing layer [5]. By mixing multiple CNT chiral structures, the optical response of the absorbing layer was tailored to approximate a theoretical complex refractive index spectrum of dielectrics; thereby enabling high solar absorptance, low infrared emittance, and a low angular dependence with a simple bilayer structure. The fabricated proof-of-concept 1-cm² absorber exhibited excellent spectral selectivity (solar absorptance/infrared emittance of 0.84/0.03), and an equilibrium temperature of ≈ 190 °C (270 °C) under nonconcentrated ($2\times$ concentrated) sunlight, considerably outperforming a blackbody-like absorber. This study presents a high-performance solar absorber with a simple planar structure and proposes a concept of designing dielectric with the desired optical properties by mixing various types of structure-sorted CNTs.

6. Generation of luminescent defects in structure-sorted carbon nanotube membranes by ultraviolet irradiation in water

Adding luminescent defects to semiconducting CNTs significantly enhances photoluminescence (PL) at photon energies lower than intrinsic PL. In this study, we found that UV irradiation in water caused moderate luminescent defect generation, significantly enhancing defect-induced PL intensity, which has potential application in optical thermometry and other fields [6].

Acknowledgement

These works were supported by JST CREST Grant Numbers JPMJCR18I5 and JPMJCR25A5, JSPS KAKENHI Grant Numbers JP22K18287, JP24H00044, JP23H01791, JP23H04874, and JP24K08253, JST FOREST Grant Number JPMJFR222N (T.N.), and the ZE Research Program, IAE (ZE2023B-43, ZE2024B-12, ZE2025B-13).

References

- [1] T. Nishihara, A. Takakura, S. Konabe, and Yuhei Miyauchi, *Commun. Mater.* 6, 89-1-89-8 (2025).
- [2] Z. Liu, T. Nishihara, V. Perebeinos, and Y. Miyauchi, *ACS Nano* 19, 41252–41260 (2025).
- [3] M. Hizukuri, H. Wu, T. Nishihara, and Y. Miyauchi, *ACS Photonics* 12, 6984–6993 (2025).
- [4] M. Hizukuri, A. Takahashi, S. Takaichi, T. Nishihara, and Y. Miyauchi, *Opt. Mater. Express* 16, 249–263 (2026).
- [5] H. Wu, T. Nishihara, M. Hizukuri, T. Tanaka, H. Kataura, and Y. Miyauchi, *ACS Photonics* 13, 1417–1427 (2026).
- [6] S. Aota, Z. Liu, T. Nishihara, and Y. Miyauchi, *Jpn. J. Appl. Phys.* 65, 022005-1-022005-5 (2026).

Collaboration Works

宮内雄平, 浙江大学(中華人民共和国), 高純度半導体型カーボンナノチューブ試料の作製とヘテロ構造化

Financial Support

1. Grant-in-Aid for Scientific Research

宮内雄平, 基盤研究(S), エネルギー科学展開に向けた量子熱光物性の基盤構築

Wu Hengkai, 特別研究員奨励費, カーボンナノチューブの量子熱光物性に基づく超高効率太陽光選択吸収体の実現

川上未央子, 特別研究員奨励費, 精密熱ふく射スペクトル制御に向けた異種ナノ物質薄膜の多重積層技術の開拓

2. Others

宮内雄平, 国立研究開発法人科学技術振興機構(CREST), ナノ物質集積半導体の熱光工学基盤確立と発電応用

松田一成, 宮内雄平, 東京都公立大学法人, 配向制御ナノチューブを基盤にした日米共同クリーンエネルギー技術開発

Publications

T. Nishihara, A. Takakura, S. Konabe, Y. Miyauchi, Thermal and nonthermal exciton light emissions from carbon nanotubes above 1000 K, *Communications Materials*, 6, 89, 2025

M. Hizukuri, H. Wu, T. Nishihara, Y. Miyauchi, Carbon nanotube-based all-dielectric near-infrared perfect absorbers, *ACS Photonics*, 12, 12, 6984-6993, 2025

Z. Liu, T. Nishihara, V. Perebeinos, Y. Miyauchi, Robust Exciton Binding Energy in Aggregated Structure-Sorted Carbon Nanotubes Revealed by Two-Photon Excitation Spectroscopy, *ACS Nano*, 19, 48, 41252-41260, 2025

M. Hizukuri, A. Takahashi, S. Takaichi, T. Nishihara, Y. Miyauchi, Broadband complex refractive index spectra of structure-sorted single-walled carbon nanotube assembly at high temperatures, *Optical Materials Express*, 16, 2, 249-263, 2026

S. Aota, Z. Liu, T. Nishihara, Y. Miyauchi, Generation of luminescent defects in structure-sorted carbon nanotube membranes by ultraviolet irradiation in water, *Japanese*

Journal of Applied Physics, 65, 2, 022005, 2026

D. Denier van der Gon, R. Pinna-Brito, Z. Liu, C.S.C. Nogueira, Y. Miyauchi, T. Pichler, O.H. Heckl, P. Ayala, HV-CVD synthesis yielding B-doped SWCNTs with a constrained diameter distribution, *Chemical Communications*, 62, 15, 4532-4536, 2026

H. Wu, T. Nishihara, M. Hizukuri, T. Tanaka, H. Kataura, Y. Miyauchi, Broadband Solar Selective Absorber with Dallenbach-Type Bilayer Structure Achieved Using Carbon Nanotube Membranes with Tailored Optical Spectra, *ACS Photonics*, 13, 15, 1417-1427, 2026

宮内雄平, 2本のナノチューブを融合する, 現代化学, 2025

Presentations

Y. Miyauchi, Exciton properties in aggregated carbon nanotubes, 247th ECS meeting, The Palais des congrès de Montréal, 2025.5.21

Y. Miyauchi, A. Takakura, T. Nishihara, K. Harano, O. Cretu, T. Tanaka, H. Kataura, Efficient coalescence of single-walled carbon nanotubes below 1000°C, 247th ECS meeting, The Palais des congrès de Montréal, 2025.5.21

Y. Miyauchi, Chemistry and photophysics in structure-sorted carbon nanotube assembly, ASPIRE-PIRE WORKSHOP on NANOTUBES2025, The University of Tokyo, 2025.6.13

宮内雄平, 低次元物質中の電子正孔系の熱光科学—宇宙・核融合・プラズマ科学との接点を探る, 第37回プラズマ科学セミナー, オンライン, 2025.7.15

宮内雄平, 炭素のナノテクノロジーで拓くエネルギー変換技術のフロンティア, 東京都教育庁指導部高等学校指導課 京都大学エネルギー理工学研究 所 見学会, 京都大学, 2025.8.20

Y. Miyauchi, High temperature luminescence of carbon nanotubes, Japan-US Network for Clean Energy Technologies Involving Oriented Nanotubes (JUNCTION) 2025, The Richardson Hotel, Buffalo, New York, United States, 2025.9.4

宮内雄平, カーボンナノ材料の量子熱光物性, 第86回応用物理学会秋季学術講演会シンポジウム「光と熱の融合が拓く機能制御の最前線」, 名城大学, 2025.9.8

宮内雄平, ナノ物質集積半導体の光学応答におけるマルチスケール物理, 日本物理学会 第80回年次

大会 シンポジウム「2.5 次元物質科学の現状と課題」, 広島大学, 2025.9.18

Y. Miyauchi, T. Nishihara, A. Takakura, S. Konabe, High-temperature nonthermal light emission from carbon nanotubes, The 69th Fullerenes-Nanotubes-Graphene General Symposium, 台湾師範大学, 台湾, 2025.9.24

Y. Miyauchi, Photophysics and chemistry of carbon nanotubes at high temperatures, Networking with Nature Nanotechnology Senior Editor, Institute for Chemical Research, Kyoto University, 2025.10.14

Y. Miyauchi, Thermal photophysics in carbon nanotubes, MANA International Symposium 2025, WPI-MANA Bldg. NIMS, 2025.10.17

Y. Miyauchi, Tailoring light-matter interaction in carbon nanotube membranes for high-temperature energy applications, Materials Research Meeting (MRM) 2025, PACIFICO Yokohama, 2025.12.9

Y. Miyauchi, High-Temperature Optical Properties of Structure-Sorted Carbon Nanotube Membranes and Their Energy Applications, Pacificchem 2025, Sheraton Waikiki, Hawaii, USA, 2025.12.15