【Grant-in-Aid for Scientific Research (S)】

Establishing a scientific foundation for harnessing quantum thermo-optical properties of nanomaterials for advanced energy conversion

Principal Investigator	Kyoto University, Institute of Advanced Energy, Professor MIYAUCHI Yuhei Researcher Number : 10451791
Project Information	Project Number : 24H00044 Project Period (FY) : 2024-2028 Keywords : nanomaterials, carbon nanotube, exciton, thermal radiation, energy conversion

Purpose and Background of the Research

●Outline of the Research

Semiconducting carbon nanotubes (CNTs) possess a distinctive quantum thermo-optical property, wherein they transform high temperature thermal energy into narrowband near-infrared light. Our research focuses on harnessing this property to enable highly efficient thermophotovoltaic power generation from both sunlight and high-temperature heat sources. The material's ultrathin structure results in an extremely strong electrical force between negative charges (electrons) and positive charges (holes) generated upon light or heat absorption. This allows the formation of stable quantum states called excitons even at temperatures exceeding 1000 K, enabling the conversion of heat into narrow-band near-infrared light with a certain range of photon energy. Leveraging this property could significantly enhance the efficiency of thermophotovoltaic power generation. This project aims to push the thermostability of carbon nanotubes and related nanomaterials beyond conventional limits, establishing a foundation for exploring and further applying their quantum thermo-optical properties in uncharted high-temperature and non-equilibrium realms.

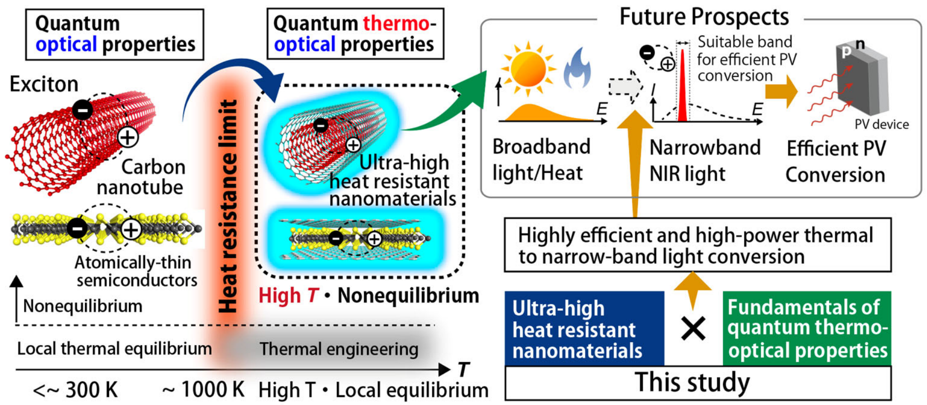

Figure 1. Outline of this project.

●Background and Objectives

Excitons are neutral quasiparticles that emerge from the binding of excited electrons and holes in solids. We have delved into the exciton properties, particularly in nanoscale materials like CNTs, focusing on their thermal behavior. Our previous research has shown that thermal excitons generated in isolated single CNTs lead to narrow-band thermal radiation in the near infrared region (see Figure 2). This remarkable quantum property at high temperatures, which converts heat into photons with well-defined energy, holds promise for applications in photon energy-selective thermal light emitters enabling high-efficiency solid-state thermal power generation.

Our recent research revealed that when CNTs are integrated into bundles for their use in macro-scale devices, their thermal stability—both for the material itself and the exciton—is reduced compared to that of a single CNT. On the other hand, our theoretical studies have shown the possibility of highly efficient thermo-photoenergy conversion beyond the conventional limit at high temperatures above 1000 K, under light irradiation.

In this project, by overcoming the current limitations in the nanomaterials' heat resistance, we seek to establish an academic foundation that explores previously uncharted realms of quantum materials science under non-equilibrium conditions, such as under light irradiation, at very high temperatures. Ultimately, the goal is to extend the temperature range over which the quantum properties of nanomaterials can be exploited to much higher temperatures, making them available for use in harsh, high-temperature energy science and technology.

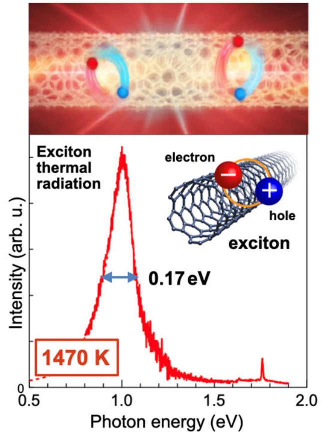

Figure 2. Diagram of thermal excitons in CNTs (top) and narrowband exciton thermal radiation spectrum (bottom).

Expected Research Achievements

●Development of ultra-high heat resistance technology for nanomaterials

This study aims to create ultra-high heat-resistant integrated nanomaterials by developing a technique for forming superior heat-resistant barrier layers (Figure 3). The goal is to make the remarkable quantum properties of nanomaterials available for advanced energy conversion technologies at high temperatures.

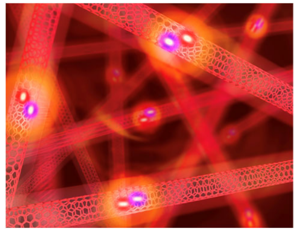
Figure 3. Diagram of ultra-high heat-resistant nanomaterial aggregates.

●Elucidation of the physics governing heat-to-light conversion processes via excitons

By conducting thermo-photophysical property measurements ranging from low to very high temperatures, we aim to elucidate the physics governing the excitonic heat-to-light conversion properties under light irradiation.

●Exploration of new excitonic thermo-optical properties of analogous nanomaterial systems

We will elucidate the excitonic thermo-optical properties of various low-dimensional nanomaterials other than carbon nanotubes (e.g., atomic layer semiconductors) and systematically clarify the differences caused by material-specific characteristics. By doing so, we aim to deepen our understanding of the science and explore further possibilities for applications.

Promotion of this research is expected to have a ripple effect on various fields of energy science and technology (see Figure 4).

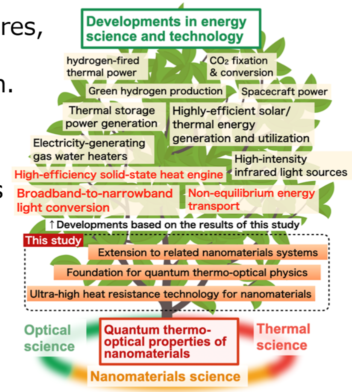

Figure 4. Scope of this study and prospects for subsequent development.

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