2-5-10. Photomechanical Crystal Materials

Overview

Photomechanical crystals are crystals that exhibit macroscopic motions such as bending when exposed to light. Over the past decade, many photomechanical organic crystals have been developed, mainly based on photochemical reactions, particularly photoisomerization. Recently, the photothermal effect and natural vibration, which exhibit high-speed bending, have been discovered as new actuation mechanisms, enabling the actuation of almost all light-absorbing crystals. Such photomechanical crystal materials are expected to find future applications in actuators and soft robotics.

Current Status and Frontline

Organic crystals are the ultimate solid materials in which molecules are regularly arranged three-dimensionally. Research on photomechanical crystals was conducted in the 1980s but was discontinued. In 2007, it was reported that when diarylethene crystals were irradiated with light, they bent due to photoisomerization. This led to active research into photomechanical crystals. Mainly based on photochemical reactions, particularly photoisomerization, many photomechanical crystals have been developed over the past decade, including diarylethene, azobenzene, salicylideneaniline, anthracene, and others. The types of motion created expanded beyond bending to include twisting, jumping, and translational movement. Unlike in solution, photoreactions within crystals proceed cooperatively due to constraints from surrounding molecules. Recently, the dynamics of photoreactions in crystals have been analyzed, clarifying the relationship between reaction propagation and crystal actuation. However, photochemical reactions do not occur in all crystals, limiting the number of crystals that can be driven photochemically. Other drawbacks include thick crystals not moving, slow motion, and irradiation being largely limited to ultraviolet light. In addition to photochemical reactions, phase transitions induced by light are another actuation mechanism for crystals. However, only a few examples have been reported, and the inability to predict whether phase transition will occur remains a difficulty.

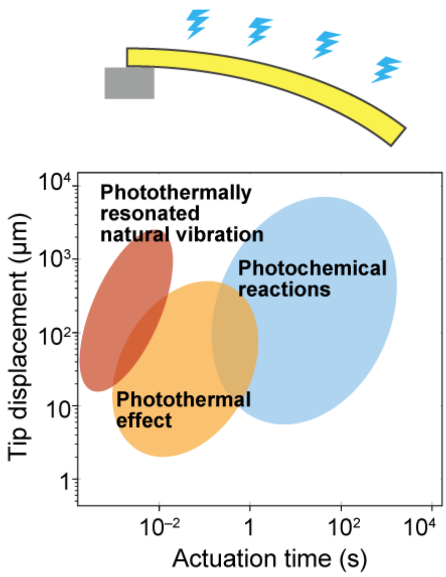

Figure 1. Actuation performance of organic crystals by photochemical reaction, photothermal effect, and photothermally resonated natural vibration.

In 2020, it was first reported that crystals bent rapidly due to the photothermal effect, in which heat is rapidly generated by the non-radiative deactivation of photoexcited species. This photothermal bending is induced by a non-steady temperature gradient in the thickness direction due to thermal conduction of heat generated near the crystal surface by light irradiation. However, photothermal bending had the drawback of small bending angle. Subsequently, in 2023, it was reported for the first time that illuminating organic crystals with light induces natural vibration. Natural vibration is a physical phenomenon in which an object continues to vibrate at its own inherent frequency (natural frequency) when an external force is once applied to it. This natural vibration arises from thermal loading due to temperature gradients within the crystal and is significantly amplified by resonance. Both the photothermal effect and natural vibration are caused in almost all light-absorbing crystals. In particular, photothermally resonated natural vibration enables high-speed and large actuation of any light-absorbing organic crystal over a wide wavelength range (from ultraviolet to near-infrared) and even with continuous light (Fig. 1). Simulations are also possible, making it possible to design actuations that were difficult to achieve with conventional photochemical reactions. Significant improvements in actuation performance were achieved, resulting in speeds several orders of magnitude faster than conventional photochemical reactions. Furthermore, it was found that organic crystals actuate faster than polymers and larger than inorganic materials demonstrating performance that bridges the gap between the two. Organic crystals have not received much attention due to their image of being hard and brittle, but as their versatility has expanded and their performance has improved, they have been recognized as useful mechanical materials. In conclusion, the research on photomechanical crystals has advanced from fundamental research to the stage of application research toward actuators and soft robotics.

References

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Future Perspectives and Directions

Challenges to be resolved or realized within the next 10 years: Development of high-performance photomechanical crystals. Establishment of methods for controlling crystal size and shape. Elucidation of the relationship between crystal photoreactions and motion. Accumulation of mechanical properties for crystals. Hybridization and integration of photomechanical crystals. Realization of commercially available AI soft robots using photomechanical crystals.

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