

Optical Motion Control of Maglev Graphite

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S Supporting Information

ABSTRACT: Graphite has been known as a typical diamagnetic material and can be levitated in the strong magnetic field. Here we show that the magnetically levitating pyrolytic graphite can be moved in the arbitrary place by simple photoirradiation. It is notable that the optical motion control system described in this paper requires only NdFeB permanent magnets and light source. The optical movement is driven by photothermally induced changes in the magnetic susceptibility of the graphite. Moreover, we demonstrate that light energy can be converted into rotational kinetic energy by means of the photothermal property. We find that the levitating graphite disk rotates at over 200 rpm under the sunlight, making it possible to develop a new class of light energy conversion system.

Diamagnetic materials having a negative magnetic susceptibility involve a repulsive force in a magnetic field, and as a result, it allows for magnetic levitation (maglev).¹ Many common materials as water, glass, metal, and plastic exhibit diamagnetism, but stable maglev is observed only under very high-magnetic field generated by superconducting magnets because of their weak negative susceptibilities.^{2–5} In contrast, some of the strongest diamagnetic materials, such as graphite and bismuth, can be levitated above NdFeB permanent magnets at room temperature.^{6,7} Since a magnetically levitating diamagnetic material without any contact can be effectively manipulated by weak forces, the passive maglev has attracted interest for its potential applications for actuator and transport systems. However, so far no practicable maglev-based actuator systems have been developed because of some problems that include low photoresponsivity and the inefficient displacement.⁸ Here we show that a levitating position can be arbitrarily controlled by taking advantage of the changes in the magnetic susceptibilities caused by the photothermal effect of a magnetically levitating material itself and that light energy can be converted into rotational kinetic energy. This achievement of optical motion control system enables the development of a three-dimensional noncontact manipulation system and opens a path to construction of a new class of solar energy conversion system.

The first stable maglev of a diamagnetic material was achieved in 1939 by Braubek.¹ Before that, it was considered that such an achievement would have been impossible, because Earnshaw's theorem states that no stationary object made of magnets in a fixed configuration can be held in stable

equilibrium by any combination of static magnetic or gravitational forces.⁹ Since 1990, some intriguing studies about diamagnetic levitation have been reported, in particular, the levitation of a live frog by Geim et al. attracted great attention.^{3,5} In recent years, the invention and spread of cheap and powerful NdFeB permanent magnets make maglev more familiar. Although the application of maglev technique to the actuator and the manipulator has been recently expected, it will take a little longer for it to be put into practical use.

The principle of diamagnetic levitation is expressed by the balance of the gravitational force (mg) and the magnetic force (F_{mag}) acting on the levitating diamagnetic material as described in eq 1:

$$mg = F_{\text{mag}} = (\chi V / \mu_0) B dB / dz \quad (1)$$

where m is the mass of the levitating object, g is the acceleration of gravity, μ_0 is the permeability of vacuum, χ is the volume magnetic susceptibility, V is the volume of object, B is the field intensity, and z is the vertical position. The balance equation can be simplified to the following eq 2:

$$\rho g \mu_0 / \chi = B dB / dz \quad (2)$$

where ρ is the density of the object. This equation means that the position of the levitating diamagnetic material can be controlled by the magnetic force field ($B dB / dz$) and the density or magnetic susceptibility of levitating diamagnetic material. To the best of our knowledge, no one has succeeded in developing a maglev-based motion control system utilizing the changes in the diamagnetic properties by an external stimulus, like temperature, light, sound, etc.

To start, we investigated the static levitation behavior of the pyrolytic graphite (PG) by changing the temperature resulting from the photothermal effect of graphite irradiated with a 405 nm diode-pumped solid-state (DPSS) laser. A schematic view of the maglev system is shown in Figure 1A. The temperature of the levitating PG disk was controlled by changing the laser power (0–260 mW). The static levitation height of the PG disk was measured by a laser displacement sensor. It is worth noting that significant changes in the levitation height could be observed for the PG disk by the light irradiation. Figure 1B shows the height of the levitating PG disk as a function of the temperature of the PG disk, which was measured by infrared thermography. The levitation height of the PG disk at 293 K is 0.592 mm and decreases in an approximately linear fashion as

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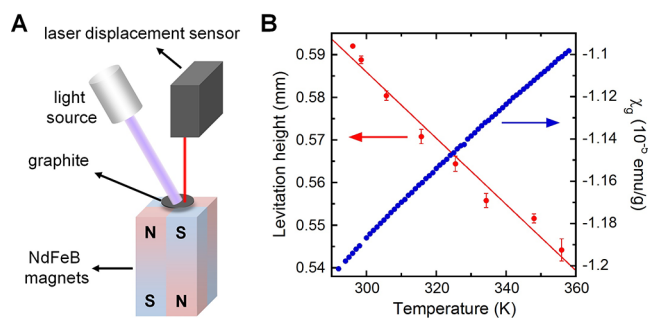


Figure 1. Control of the levitation height of the PG disk using photothermal effect. (A) Experimental setup for the measurement of the levitation height. The device consists of four 500 mT NdFeB magnets ($3 \times 3 \times 10$ mm) arranged to face in alternate directions. The PG disk is 3 mm (0.40 mg) in diameter. The light source is a DPSS laser with a wavelength of 405 nm and a power of 300 mW. (B) Temperature dependence of levitation height and magnetic susceptibility.

the temperature is increased. This behavior clearly suggests that the decrease in the levitation height is caused by the changes of the magnetic susceptibility of the PG rather than volume increase with a rise in temperature. In fact, as shown in Figure 1B, the magnetic susceptibility of the PG dramatically increases with increasing temperature as previously reported.¹⁰ The photoinduced changes of the magnetic susceptibility of the PG can be attributable to the increase in the number of thermally excited electrons.¹¹

The photothermal effect of the PG on the magnetic susceptibility was investigated by measuring electron spin resonance (ESR) spectra to discuss the details of the photoresponse processes. The ESR spectrum for the PG measured in the dark at 293 K is depicted in Figure 2A. The ESR line shape exhibits the so-called Dysonian form indicating a conducting behavior of the PG.¹¹ The differences in the ESR intensities from the intensities measured in the dark at 273 K were plotted as a function of the light intensity and temperature in Figure 2B. It was revealed that the ESR signal intensity increases with increasing temperature, as reported in the previous work,¹² and depends on the intensity of the irradiation light. This result clearly demonstrates that the ESR signal of the light-irradiated PG increases due to the increase in the thermally excited electrons with increasing temperature arising from the photothermal effect. Figure 2C–E shows the ESR intensity, which is obtained by subtraction of the intensity in the dark from that under photoradiation, as a function of time. After the initiation of either the light-on or -off event, it takes ~ 2 sec until the signal intensity reaches a plateau (Figure 2C). This result suggests that the PG is sensitive to light stimulation. When the light was periodically turned on and off, a fully reversible switching behavior was observed (Figure 2D). Moreover, during the prolonged photoradiation (~ 12.5 min), no significant change in the signal intensity was observed, indicating that PG has superior durability against prolonged light exposure (Figure 2E).

The photothermal response of the levitating PG disk was evaluated by infrared thermography. Figure 2F shows a schematic illustration of the experimental setup for the infrared thermography measurement. The 405 nm DPSS laser aimed at the center of PG disk. Thermograms were recorded after the initiation of either the light-on or -off event every 33 ms. The thermographic images with a temperature scale are shown in

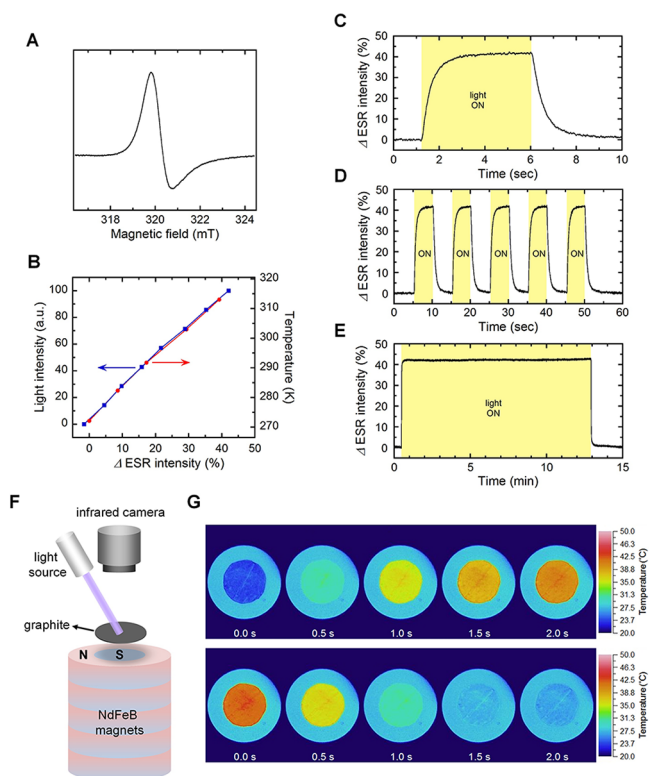


Figure 2. Photothermal and photoresponse properties of the PG. (A) ESR spectrum of the PG at $\theta = 65^\circ$ at 293 K under vacuum, where θ corresponds to the angle ($^\circ$) between the magnetic field and c axis of the PG. (B) Dependence of the differences in the ESR intensities of the PG on the intensity of the irradiation light and temperature. (C–E) Time profiles of the differences in the ESR intensity with switching of the light irradiation from the intensity measured in the dark for the PG at 273 K. (F) Schematic illustration of the experimental setup for photothermal evaluation. An array of NdFeB magnets is comprised of five small central cylinder magnets ($\phi 8 \times 4$ mm; 400 mT) encircled by five concentric ring magnets ($\phi 19 \times \phi' 8.1 \times 4$ mm; 348 mT) of opposite magnetization. The PG disk is 10 mm (3.92 mg) in diameter. The light source is a DPSS laser with a wavelength of 405 nm and a power of 300 mW. (G) Montage of infrared images of the levitating PG disk under laser irradiation (top) and after the termination of irradiation (bottom) at room temperature (see movies S1 and S2).

Figure 2G. As a result, a significant temperature increase of ca. 20°C was observed. It is noteworthy that the time scale for the photothermal response is in good agreement with that for the photoresponse of the ESR signal intensity in Figure 2C. The meaningful temperature increase by the laser irradiation should be attributed to significant differences in the thermal conductivity (λ) between the PG disk and air ($\lambda_{\text{PG}} = 1600 \text{ W m}^{-1} \text{ K}^{-1}$ and $\lambda_{\text{air}} = 0.0241 \text{ W m}^{-1} \text{ K}^{-1}$), although graphite has an exceptionally good heat release property, enough to be used as a heat sink.

Moreover, we attempted to drive the levitating PG disk by direct irradiation with the laser light of 405 nm to the PG disk. As shown in Figure 3A,B, in the case of moving the light source in any direction, the levitating PG disk can be driven in the same direction as the light beam (movies S3 and S4). Such a noticeable phenomenon can be explained as follows: (i) If the irradiated site is moved from the center of the PG disk to the edge of the disk, then the distribution of the PG disk temperature will be changed as discussed below; (ii) the magnetic susceptibility of the PG disk around the irradiated site

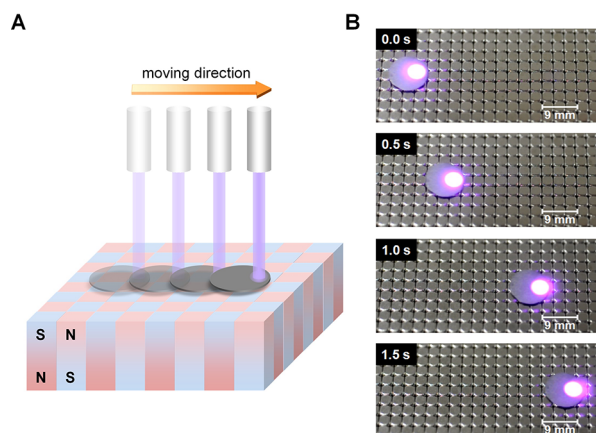


Figure 3. Arbitrary control of the moving direction of the floating PG disk by a laser. (A) Experimental setup for magnetic levitation stage. The stage consists of 500 mT NdFeB magnets ($3 \times 3 \times 10$ mm) arranged to face in alternate directions. PG disk is 10 mm (3.92 mg) in diameter. The light source is a DPSS laser with a wavelength of 405 nm and a power of 300 mW. (B) Photographic frames of the linear motion of the PG disk in one direction (movie S3).

increases with increasing the temperature; (iii) repulsion force felt by the PG disk is partially changed so that it gets off balance and incline; (iv) the PG disk moves in the direction of the tilt; and (v) the irradiation site gets back from the edge of the disk to the center of the disk. Repeating these processes enables motion control of the levitating PG disk. As shown in Figure 3B, the maximum velocity was estimated to be around 45 mm s^{-1} . To the best of our knowledge, this is the first achievement of a maglev-based real-time motion control system.

Finally, we have experimentally demonstrated the possibility to develop a new energy system. Intriguingly, the levitating PG disk above 'cylinder' type magnets (Figure 2F) begins to rotate during light irradiation at the edge of the PG disk (Figure 4A). The rotational speed was estimated to be around 20 rpm. Judging from the infrared thermography images for the rotating disk system, it is considered that distorted distribution of the temperature of the PG disk triggers the rotatory motion (Figure 4B). The levitating PG disk is displaced toward the irradiated site immediately after photoirradiation. At this moment, the levitating PG disk feels the repulsive force from the magnetic potential wall. Ideally, the repulsive force works in opposite direction to the movement direction. However, the actual repulsive force vector could deviate a little from the center of gravity line due to heterogeneity of the magnetic field generated from the NdFeB magnets. Therefore, the force acting toward the tangent to the PG disk is generated. In fact, the direction or the speed of rotation depends on the photoirradiation positions (movie S8). Such a behavior was also observed under sunlight (movie S9), it was revealed that the maximum rotational speed of the PG disk was reached over 200 rpm, indicating that it is possible to apply it to an optical driven turbine, flywheel, and so on.

In conclusion, we have developed an innovative actuator system that allows three-dimensional motion of a magnetically levitating diamagnetic material to control in real-time at ambient temperature using only light for a power source. The motion of the magnetically levitating diamagnetic object can be controlled by the changes in magnetic susceptibility arising from an efficient photothermal effect. Another important finding is that this optically driven maglev system can convert

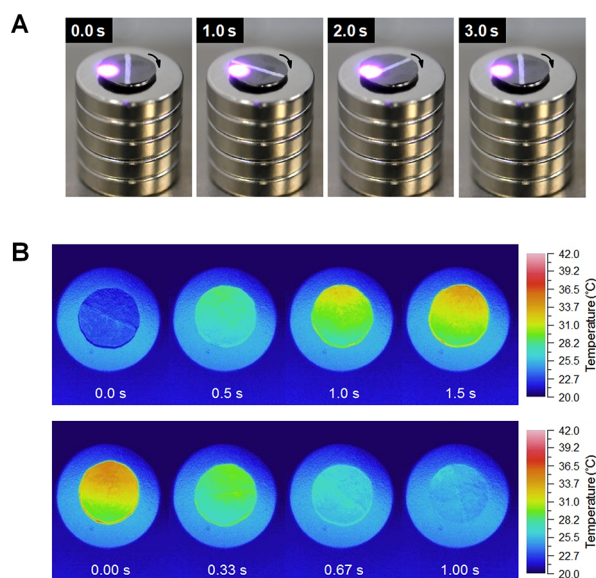


Figure 4. New photoenergy conversion system based on magnetic levitation. The experimental setup for the arrangement of the magnets and the condition of the light irradiation are the same described in Figure 2F caption. (A) Photographic frames of the rotatory motion of the PG disk in a clockwise direction (movie S5). (B) Montage of infrared images of the levitating PG disk under laser irradiation (top) and after the termination of irradiation (bottom) at room temperature (movies S6 and S7).

solar energy into rotational energy. We believe that these findings open up great possibilities for a next-generation actuator or a photothermal solar energy conversion system.

■ ASSOCIATED CONTENT

📄 Supporting Information

Experimental details and supplementary movies S1–S9. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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Notes

The authors declare no competing financial interest.

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