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研究課題名（和文） Fabrication and characterization of a single-VO2-nanoparticle electronic nano-switch device

研究課題名（英文） Fabrication and characterization of a single-VO2-nanoparticle electronic nano-switch device

研究代表者

Ｐｉｎ　Ｃｈｒｉｓｔｏｐｈｅ (Pin, Christophe)

北海道大学・電子科学研究所・助教

研究者番号： ５０７９３７６７

交付決定額（研究期間全体）：（直接経費）　　3,300,000円

研究成果の概要（和文）： VO2ナノ粒子の光操作は初めて研究された。集光ガウス又はラゲールガウスビームを用いて、VO2の熱誘起相転移による非線形光学トラッピングが実証された。円偏光を用いて、捕捉された粒子の軌道回転が達成された。スピン・軌道角運動量変換機構は、ミー共鳴による指向性散乱光に依存することがわかった。VO2ナノ粒子の成長中に回転方向が反転することが実証された。
レーザー誘起水熱合成により、アルミナコート金薄膜上に1μm大のVO2マイクロディスクを作製した。プラズモン支援水熱合成により、金-VO2ヘテロナノ構造（金ナノディスク上のVO2ナノシェル）を作製した。プラズモン共鳴によるVO2合成の促進が実証された。

研究成果の学術的意義や社会的意義
New fabrication techniques of vanadium dioxide (VO2) nanodevices are important for the fabrication of ultrafast, low-energy electronic or optical switching devices. New optical manipulation techniques are important to further understand interactions between light and nanoparticles.

研究成果の概要（英文）： Optical manipulation of vanadium dioxide (VO2) nanoparticles was investigated for the first time. Nonlinear optical trapping due to the heat-induced phase transition of VO2 was demonstrated using focused Gaussian and Laguerre-Gaussian beams. Orbital rotation of trapped particles was achieved by using a circularly polarized laser beam. The spin-to-orbital angular momentum conversion mechanism was found to rely on the directive light scattering induced by Mie resonances. Rotation direction control was achieved, and rotation direction reversal was demonstrated during the growth of VO2 nanoparticles.
Laser-induced hydrothermal synthesis of VO2 was used to fabricate 1-micrometer-large VO2 microdisks on alumina-coated gold thin films. Gold-VO2 hetero-nanostructures (VO2 nanoshell on gold nanodisks) were fabricated by plasmon-assisted hydrothermal synthesis of VO2. Plamonic-resonance-induced enhancement of the vanadium oxide synthesis was demonstrated.

研究分野： Optics

キーワード： vanadium dioxide　Mott transition　nonlinear optical force　spin-orbit coupling　nanoparticle rotation　hydrothermal synthesis　plasmonic nano-switch

１．研究開始当初の背景

(1) Optical trapping of nanoparticles using plasmonic nanogap antennas was demonstrated. At high laser intensity, the trapped particles can be adsorbed at the surface of plasmonic nanostructures, especially in or on the nanogap of dimer nanoantennas. *[C. Pin et al. ACS Omega 2018]* This technique could be applied to fabricate hetero-nanostructures.

(2) Electronic switching devices made of vanadium dioxide (VO_2) were recently demonstrated. It was shown that the length of the VO_2 junction is a key parameter to achieve an ultrafast, low-energy-level electronic response. New techniques are therefore needed to integrate VO_2 elements in nanogap structures.

２．研究の目的

(1) Fabrication of hetero-nanostructures made of gold and VO_2 for nano-optic and nano-electronic applications. The original target was the realization of a single-VO_2-nanoparticle switching device that can be both optically and electrically triggered. Due to the new findings achieved during this project, the demonstration of an electronic switching device was postponed and temporarily replaced by the realization of tunable plasmonic nanostructures.

(2) Additional objective 1: Study of the impact of the insulator-to-metal phase transition (IMT) on the optical trapping of VO_2 particles.

(3) Additional objective 2: Demonstration of a new optical manipulation technique based on spin-to-orbital angular momentum conversion caused by light-matter interactions.

３．研究の方法

(1) Plasmonic nanogap antennas were designed by numerical simulation and fabricated by electron-beam lithography technique. An aqueous dispersion of purchased VO_2 nanoparticles (average diameter 60 nm) was used to conduct plasmonic trapping experiments. After several unsuccessful attempts at trapping VO_2 nanoparticles using gold plasmonic nanostructures, photothermal heating was identified as a major issue and plasmonic trapping experiments were stopped. A thorough review of the scientific literature on optical trapping using photonic and plasmonic nanostructures was published to summarize the results of the bibliographic work. *[C. Pin et al. J. Photochem. Photobiol. C 2022]*

(2) The optical trapping of VO_2 nanoparticles and microparticles dispersed in ultrapure water was studied using a conventional near-infrared (NIR) optical tweezers setup. The influence of the laser power, polarization state, beam intensity profile, and orbital angular momentum was investigated using Gaussian, line-shaped Gaussian, and Laguerre-Gaussian (LG) beams.

(3) Hydrothermal synthesis reaction of VO_2 was studied as an alternative way to fabricate gold-VO_2 hetero-nanostructures. An aqueous solution composed of vanadium pentoxide V_2O_5, oxalic acid, and sulfuric acid was prepared and used as precursor solution. Laser-induced hydrothermal synthesis of VO_2 was performed by irradiating a NIR laser on gold-coated and gold+alumina-coated glass coverslips. Gold-VO_2 hetero-nanostructures were fabricated by plasmon-assisted hydrothermal synthesis of VO_2 by irradiating a NIR laser on alumina-coated gold nanostructures. Samples were analyzed by SEM observations and EDS measurements. Hydrothermal growth of optically trapped VO_2 nanoparticles was also investigated to evidence the IMT of the synthesized materials.

４．研究成果

(1) Plasmonic trapping was found inefficient in the assembly of VO_2 nanoparticles on gold nanogap structures. Photothermal heating in both gold and VO_2 was identified as the main issue that prevents the nanoparticles to reach the nanogap structure during the trapping experiments. VO_2 nanoparticle trapping was not achieved even after optimization of the shape of the plasmonic nanoantenna to reduce the temperature increase.

(2) VO_2 nanoparticles was successfully trapped in water by focusing a NIR laser beam near the surface of a glass coverslip. It was demonstrated that IMT induces nonlinear optical

forces due to photothermal heating. Unlike other dielectric or metallic nanoparticles, VO_2 particles were trapped away from the maximum of light intensity and followed an orbital trajectory around the center of the focused Gaussian beam (Fig. 1a). The following mechanism was proposed (Fig 1b): When the dielectric (insulator state) particle is attracted by the optical force, its temperature increases due to the increasing light intensity. When the temperature threshold is reached, the IMT induces a reversal of the optical force direction, and the metallic-state particle is repelled from the high intensity region. The particle is thus trapped at locations where the phase transition occurs. The nonlinearity of the optical force acting on VO_2 was also confirmed by numerical simulation performed using the software COMSOL Multiphysics. Due to the rotational symmetry of the beam intensity, orbital trajectories are observed. For the same reason, 2 orbital trajectories are observed when a LG beam (topological charge ±2) is used: one trajectory inside and another one outside the high-intensity region of the ring intensity profile (Fig. 1c).

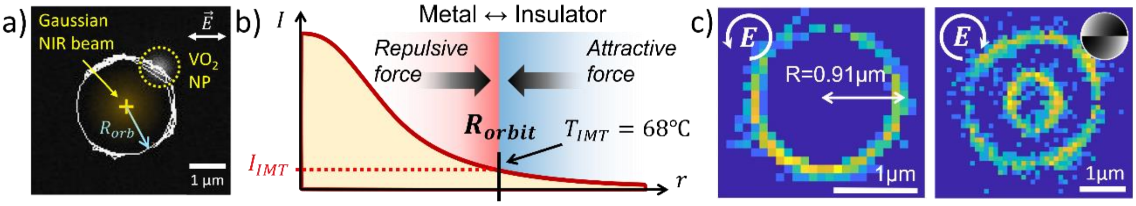

Fig. 1: a) Dark-field image of a trapped VO_2 nanoparticle. White curve: Orbital trajectory of the particle around the center of the focused Gaussian laser beam. b) Proposed mechanism: When the trapped particle come close enough to the beam center (Gaussian intensity profile), photothermal heating induces the IMT and the optical force direction is reversed. c) Position histograms of a particle trapped using a Gaussian beam (left) and a LG beam (right).

(3) Control of the orbital rotation direction of the trapped VO_2 particles was achieved by using a circularly polarized incident laser beam. When reversing the circular polarization direction, the particle rotation direction was also reversed. Numerical simulations results evidenced that this spin-to-orbital angular momentum conversion is caused by the excitation of multiple Mie resonances leading to directive light scattering. It was shown by numerical simulation that reversal of the rotation direction can occur in the case of insulator-state particles with only few Mie resonances (Fig. 2). The size-/material-phase-dependency of the rotation direction was found to influence the orbital rotation direction of optically trapped vanadium oxide particles during their hydrothermal growth in a precursor solution.

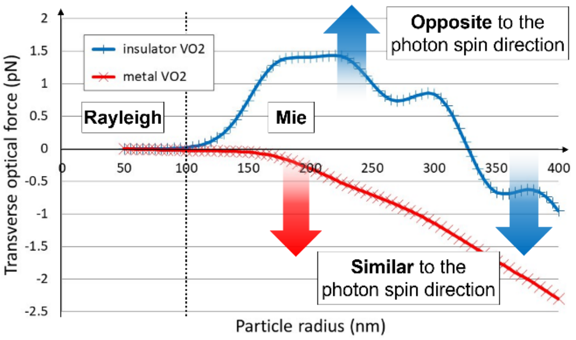

Fig. 2: Numerical estimation of the transverse force acting on a VO_2 particle as a function of its size and phase.

(4) Laser-induced hydrothermal synthesis of VO_2 was demonstrated for the first time. A 3 nm-thick alumina coating was used as adhesion layer to enable the fabrication of VO_2 on gold. 1-µm-large were fabricated on gold thin films (Fig. 3a,c). Improved crystallization (higher annealing temperature) was achieved when a microbubble was formed. Vanadium oxide nanoshells were fabricated on gold nanodisks (Fig. 3b). Plamonic-resonance-induced enhancement of the vanadium oxide synthesis was demonstrated.

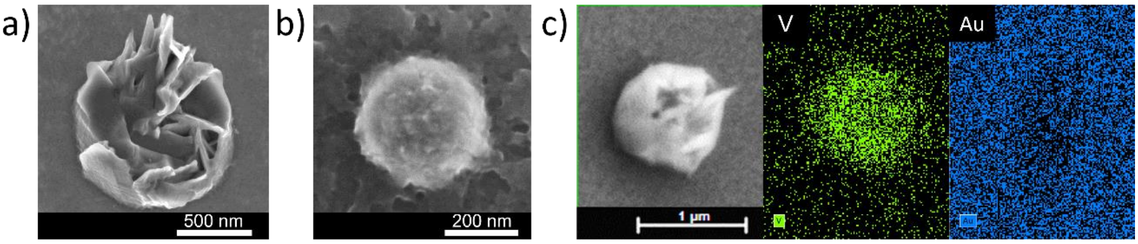

Fig. 3: SEM pictures of a) a VO_2 microdisk fabricated on an alumina-coated gold thin film and b) a VO_2 shell fabricated on an alumina-coated gold nanodisk (radius 345 nm). c) SEM picture of a VO_2 microdisk on alumina-coated gold thin film, and vanadium and gold concentration maps obtained by EDS measurements.

５．主な発表論文等

〔雑誌論文〕　計7件（うち査読付論文　3件／うち国際共著　7件／うちオープンアクセス　1件）

１．著者名 Fujiwara Hideki, Sudo Kota, Sunaba Yuji, Pin Christophe, Ishida Shutaro, Sasaki Keiji	４．巻 21
２．論文標題 Spin－Orbit Angular-Momentum Transfer from a Nanogap Surface Plasmon to a Trapped Nanodiamond	５．発行年 2021年
３．雑誌名 Nano Letters	６．最初と最後の頁 6268-6273
掲載論文のDOI（デジタルオブジェクト識別子） 10.1021/acs.nanolett.1c02083	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 Pin Christophe, Fujiwara Hideki, Suzuki Tatsuro, Sasaki Keiji	４．巻 11696
２．論文標題 Photothermal energy conversion in plasmonic nanoantennas as a new path for the local growth of ZnO in nanophotonic devices	５．発行年 2021年
３．雑誌名 Proceedings SPIE	６．最初と最後の頁 116960H
掲載論文のDOI（デジタルオブジェクト識別子） 10.1117/12.2577176	査読の有無 無
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 Pin Christophe, Otsuka Ryohei, Sasaki Keiji	４．巻 11637
２．論文標題 Nanodiamond optical sorting at the femtonewton scale inside a tapered glass capillary	５．発行年 2021年
３．雑誌名 Proceedings SPIE	６．最初と最後の頁 116370Q
掲載論文のDOI（デジタルオブジェクト識別子） 10.1117/12.2577160	査読の有無 無
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 Pin Christophe, Otsuka Ryohei, Sasaki Keiji	４．巻 11926
２．論文標題 Tapered glass capillaries for the optical manipulation and sorting of nanoparticles: practical considerations	５．発行年 2021年
３．雑誌名 Proceedings SPIE	６．最初と最後の頁 119260X
掲載論文のDOI（デジタルオブジェクト識別子） 10.1117/12.2616160	査読の有無 無
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 Pin Christophe, Fujiwara Hideki, Sasaki Keiji	4．巻 52
2．論文標題 Controlled optical manipulation and sorting of nanomaterials enabled by photonic and plasmonic nanodevices	5．発行年 2022年
3．雑誌名 Journal of Photochemistry and Photobiology C: Photochemistry Reviews	6．最初と最後の頁 100534～100534
掲載論文のDOI（デジタルオブジェクト識別子） 10.1016/j.jphotochemrev.2022.100534	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 Pin Christophe、Fujiwara Hideki、Sudo Kota、Kakuta Ryo、Sunaba Yuji、Ishida Shutaro、Sasaki Keiji	4．巻 12479
2．論文標題 Nanoparticle orbital rotation, from a nanoscale plasmonic hotspot to the periphery of a laser beam	5．発行年 2022年
3．雑誌名 Proceedings SPIE	6．最初と最後の頁 124790X
掲載論文のDOI（デジタルオブジェクト識別子） 10.1117/12.2659394	査読の有無 無
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オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

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3．学会等名 SPIE Photonics West (Advanced Fabrication Technologies for Micro/Nano Optics and Photonics XIV)（国際学会）
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４．発表年 2023年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

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６．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

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