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Supporting Information

Disk-Like Nanojets with Steerable Trajectory Using Platinum Nozzle Nanoengines

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ESI Videos:

ESI Video 1 Circular motion of the nanojet with one off-center Pt nozzle nanoengine.

ESI Video 2 Linear motion of the nanojet with two identically and symmetrically distributed Pt nozzle nanoengines.

Equipment:

1. Advanced Vacuum/vision 310 MK II: gas 1 5% SiH_4/N_2 and flow rate 160 sccm, gas 2 N_2O and flow rate 1420 sccm, gas 3 N_2 and flow rate 240 sccm, pressure 800 mTorr, temperature 300◦ C;
2. Fumehood for KOH etching: temperature 120◦ C;
3. Karl Suss Deltta VPO Primer: temperature 100◦ C;
4. Cee Spin Coater: speed 5000 rpm, spin duration 30 s;
5. Karl Suss MA56 mask aligner: expose type vacuum, expose time 5 s, power 275W;
6. Fumehood for photoresist development: room temperature;
7. Semitool/PSC-101 drying machine: speed 1600 rpm, spin duration 2 min;
8. Hot Plate/MODEL HP50: temperature 100◦ C;
9. Hyper HAD color video camera;
10. Mitatoyo WF microscope: magnification 10;
11. HITACHI S-3500N scanning electron microscope: voltage 5 kV;
12. Magnetron sputter system: gas Ar and flow rate 20 sccm, base vacuum 3 mTorr, power 200W;
13. E-beam evaporator/EDWARDS FL 400: gas N_2, current 25 mA, voltage 4.96 kV, temperature RF, pressure 3.2 mTorr;
14. JEOL JSM-5600LV field emission scanning electron microscope: voltage 20 kV.

Materials:

1. Sulfuric acid (purchased from Tee Hai Chem Pte Ltd, Singapore);
2. HMDS (purchased from Clariant Pte Ltd, Singapore);
3. Photoresist 7220 (purchased from AZ Electronic Materials, Singapore);
4. AZ 300MIF developer (purchased from AZ Electronic Materials, Singapore);
5. N_2 gas (purchased from Soxal, Singapore);
6. Gold (purchased from Analytic Technologies Pte Ltd, Singapore);
7. Nickel (purchased from MOS Group, Singapore);
8. Platinum (purchased from MOS Group, Singapore);
9. Acetone (purchased from Avantor Performance Materials, USA);

10. Iso-propyl alcohol (purchased from Avantor Performance Materials, USA);
11. Potassium hydroxide (purchased from Aik Moh Paints & Chemicals Pte Ltd, Singapore);
12. Hydrogen peroxide (purchased from Tee Hai Chem Pte Ltd, Singapore).

Software

1. SEMICAPS 2200C_3 imaging system;
2. Osprey swiftcap video capturing;
3. INCA software;
4. ImageJ.

Derivation of the driving force F_{drive} stemmed from the momentum change

Generally, H_2O_2 can decompose into H_2O and O_2 molecules by the catalysis of Pt.[1,2] During the H_2O_2 decomposition, O_2 bubbles are generated and detached from the surface of the Pt nozzle nanoengines of the Au-Ni-Pt naojets. SI Figure S-1 demonstrates two states of an integrated Au-Ni-Pt nanojet-oxygen bubble system. In the beginning, O_2 bubbles are attached to the surface of the Au-Ni-Pt nanojets, called the growing state, in which the nanojets and O_2 bubbles have the joint velocity of v_1. After a period of time of Δt, O_2 bubbles are detached from the Pt-surface, called the detaching state. At this state, the Au-Ni-Pt nanojets have a velocity of v_2, while the O_2 bubbles have a distinct velocity, named v_0. According to the Momentum Conservation Law, one can obtain the following equation

$$(m + \Delta m)v_1 = mv_2 - \Delta m v_0$$

(SI-1)

$$m(v_2 - v_1) = \Delta m(v_1 + v_0)$$

(SI-2)

where, m is the mass of one single Au-Ni-Pt nanojet, Δm represents the mass of each individual detached O_2 bubble.

According to the Momentum Theorem, the driving force F'_{drive} induced by one single detached O_2 bubble can be expressed as

$$F'_{drive} = m\frac{v_2 - v_1}{\Delta t} = \Delta m\frac{v_1 + v_0}{\Delta t}$$

(SI-3)

After a period of time of Δt, N O_2 bubbles are detached from the Pt-surface of the Au-Ni-Pt nanojets. Thus, the total driving force F_{drive} can be described as

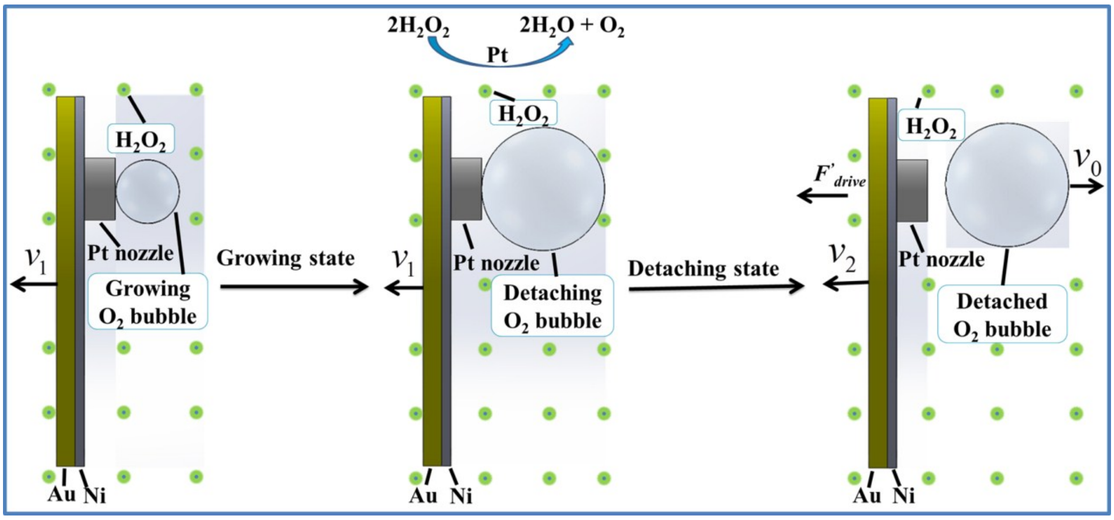
$$F_{drive} = NF'_{drive} = N\frac{\Delta m}{\Delta t}(v_1 + v_0)$$

(SI-4)

At steady state, the Au-Ni-Pt nanojets reach a constant velocity of v, namely $v_1 = v_2 = v$. Thus, one can obtain

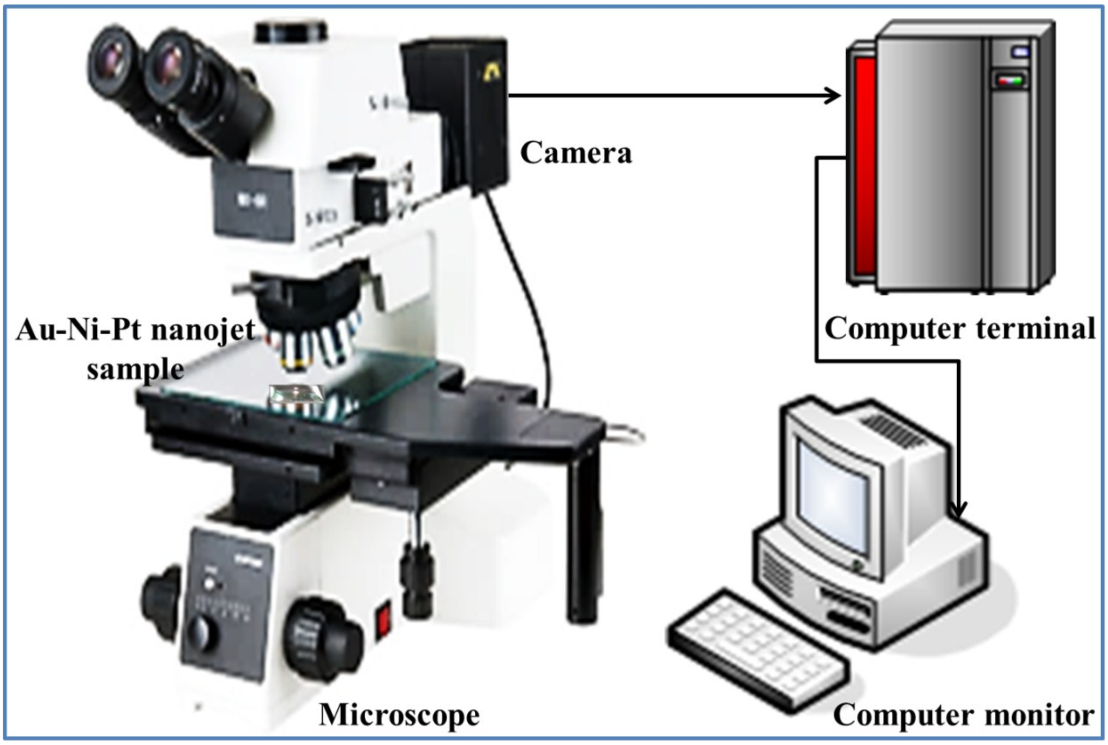
$$F_{drive} = N\frac{\Delta m}{\Delta t}(v + v_0)$$

(SI-5)



SI Figure S-1. Schematic diagram for illustrating the generation of the driving force F_{drive} induced by the detachment of the O_2 bubbles.

Experimental set-up



SI Figure S-2. Microscopy set-up for characterizing and recording the disk-like Au-Ni-Pt nanojet's steerable propulsion in aqueous H_2O_2 solution. The set-up was mainly composed of a microscope, sample, camera and computer.

The experimental set-up, as shown in SI Figure S-2, was established for investigating the nanojet's motion. The set-up was mainly composed of four parts, which were an optical microscope, sample, camera and computer.

Brownian motion speed of the Au-Ni-Pt nanojets

In micro and nano regime, the linear diffused distance x of an object can be described as in one dimensional space[3]

$$<x^2>=2Dt_{diff} \qquad \text{(SI-6)}$$

where, x, D and t_{diff} are the diffusion distance, diffusivity and diffusion time of the object, respectively. By differentiating equation (SI-6), one can obtain that the Brownian motion speed v_B is described as

$$v_B=\frac{D}{\sqrt{2Dt_{diff}}} \qquad \text{(SI-7)}$$

Moreover, Einstein and Smoluchowski showed that the diffusivity D of the object moving in a specific fluid is related to the coefficient of the friction f, and the diffusivity can be expressed as[4]

$$D = \frac{K_b T}{f} \tag{SI-8}$$

where, k_b=1.3806488×10^{-23} m^2·kg/(s·K) is the Boltzmann constant and T is the absolute temperature. The coefficient of the friction can be expressed as[3]

$$f = 6\pi\mu a \tag{SI-9}$$

where, $\mu = 0.001$ kg/(m · s) is the dynamic viscosity of the media (DI water) and a is the effective length of the object. If t_{diff} = 1 s and T=300 K, the Brownian motion speed of the fabricated Au-Ni-Pt nanojets is as follows

$$v_B \approx 0.096\ \mu\text{m/s} \tag{SI-10}$$

References

1 W. F. Paxton, K. C. Kistler, C. C. Olmeda, A. Sen, S. K. St. Angelo, Y. Cao, T. E. Mallouk, P. E. Lammert, V. H. Crespi, *J. Am. Chem. Soc.*, 2004, **126**, 13424-13431.

2 S. Wang and N. Wu, *Langmuir*, 2014, **30**, 3477-3486.

3 T. Mirkovic, N. S. Zacharia, G. D. Scholes and G. A. Ozin, *Small*, 2010, **6**, 159-167.

4 D. Patra, S. Sengupta, W. Duan, H. Zhang, R. Pavlick and A. Sen, *Nanoscale*, 2013, **5**, 1273-1283.