Supplementary Information

Remotely Powered Self-Propelling Particles and Micropumps Based on Miniature Diodes

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Description of the supplementary movies provided

All movies are real time except Movie M7 (double-speed) and in WMV format. The semiconductor devices on Movies M1-M6 float in a large Petri dish full of 10^{-6} M NaCl solution. Two AC-powered electrodes from thin wire are placed above and below (or left and right) of the scale. E_{ext} was 120 V/cm and the frequency was 1 kHz. The scale on the back is spaced at 1 cm in movies M1 to M3, M6 and at 0.5 cm in movies M4 to M5.

Supplementary Movie M1_zoom_moving_diode.wmv

A 1-mm long semiconductor diode propels to the right when the field is turned on. Field direction is horizontal.

Supplementary Movie M2_diode_small.wmv

A low magnification view of a miniature diode propelling. The diode (small speck near the bottom of the first frame) covers a distance of almost 5 cm in about 43 s. Field direction is vertical.

Supplementary Movie M3_LED_up_down.wmv

Two LEDs orient vertically when the field is turned on, light up and begin propelling. Note that the diodes move in opposite directions because they are oriented oppositely with respect to their electrode polarity.

Supplementary Movie M4_Diode_gear.wmv

"Diode-powered gear" begins rotating when the field is applied due to the directional propellant force of the diodes attached around the O-ring.

Supplementary Movie M5_LED_gear.wmv

LED-powered gear without external illumination. The diodes rotate the gear and light up - note that the lit diodes are always to the left and right of the gear as they are the ones receiving most power from the surrounding vertical field.

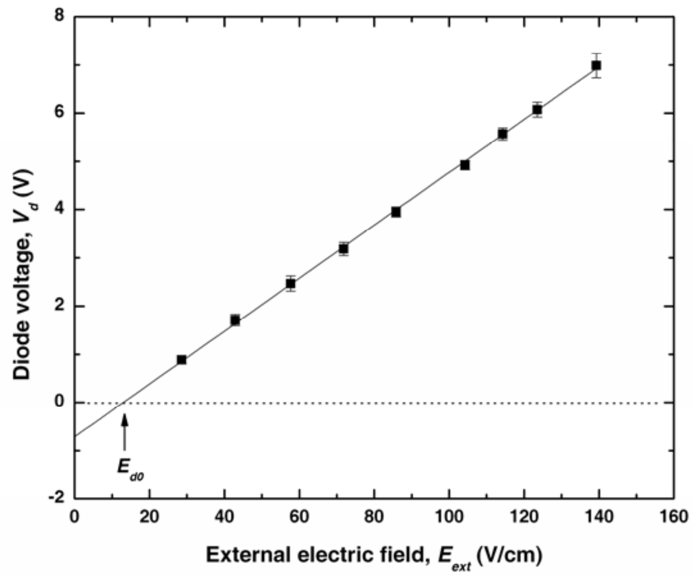
Supplementary Movie M6_Photodiode_light_control.wmv

Motility of photodiodes controlled by exposure to light (from laser pointer). The photodiode velocity drops sharply when they are illuminated and is restored when the light is turned off.

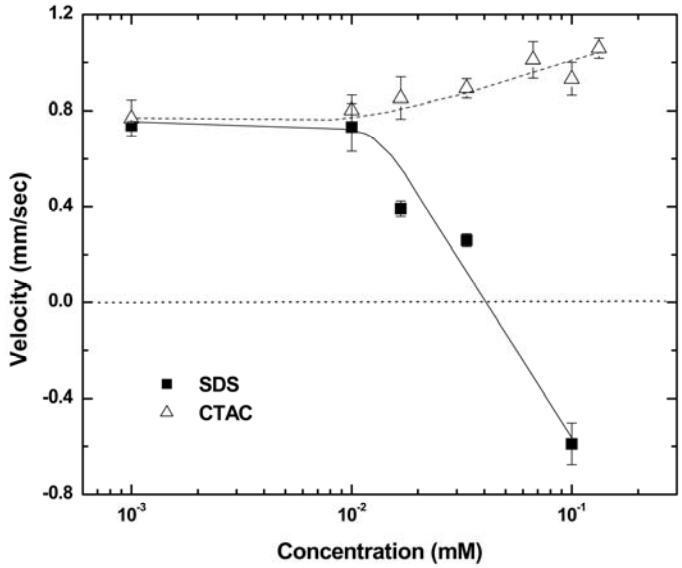
Supplementary Movie M7_AC_DC_Decoupling.wmv

Separation of two types of particles within the channel of the microfluidic device in Figure 1. At first, only an AC field is applied and both types of particles rapidly move to the right by diode pump driven flow. However, under the simultaneous action of balanced AC + DC external fields, the small particle (1 μm amidine-stabilized latex) very slowly moves to the right, while the large particle (2 μm sulfate-stabilized latex) begins moving to the left. Compare with Figure 5.

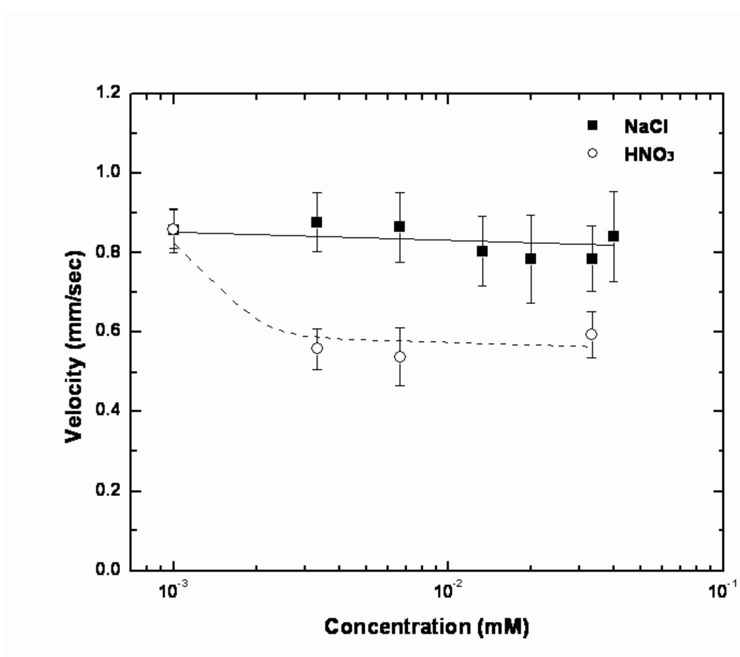
Additional experimental data



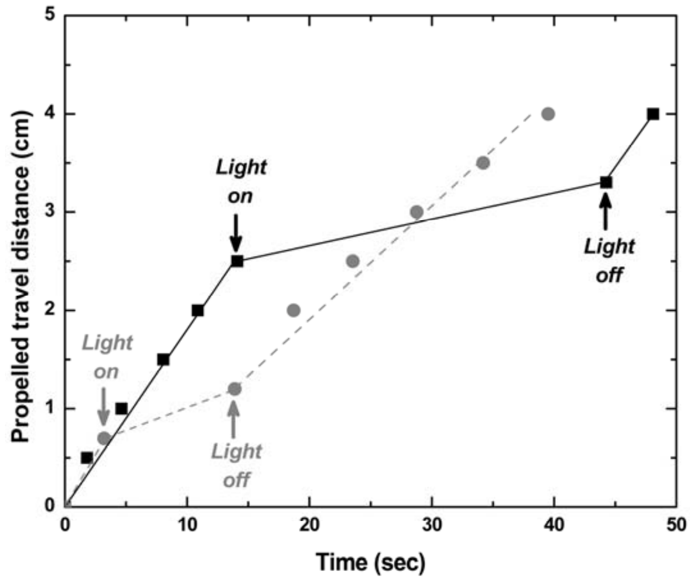
Supplementary Figure S1. Voltage generated across a fixed diode as a function of the external electric field E_{ext}. Two electrodes with 1 mm gap between them were brought in contact with the surface of the water solution of 10^{-6} M NaCl in the experimental vessel. DC voltages, V_d, induced across the diode were measured at a frequency of 1 kHz. The line is the least squares fit of the data and allows estimating the value of E_{d0}. The related value of offset voltage (≈ 0.7 V, intercept with y-axis) is in good agreement with typical specifications of silicon diodes.



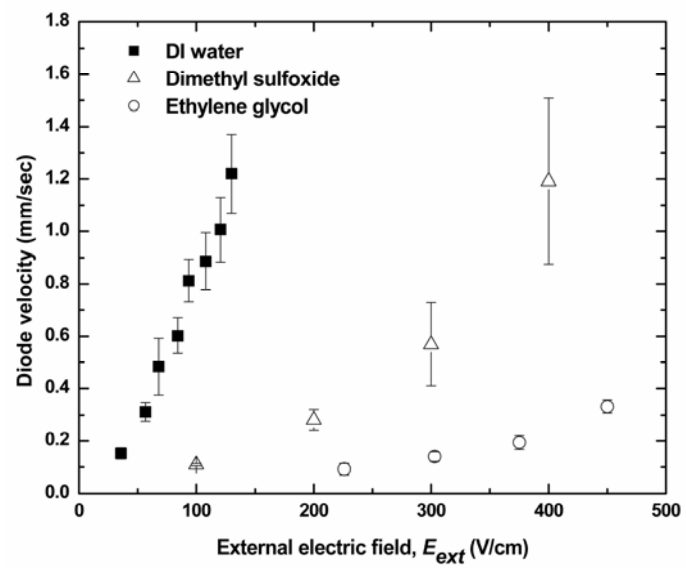
Supplementary Figure S2. Velocity as a function of the concentration of surfactants. Positively charged surfactant (CTAC) leads to small increase of the velocity by increasing the surface charge. Negatively charged surfactant (SDS) decreases the positive surface charge of the diode to the extent that the charge is reversed and the diode begins moving in the opposite direction. Experiments were performed at E_{ext} = 93 V/cm and 1 kHz.



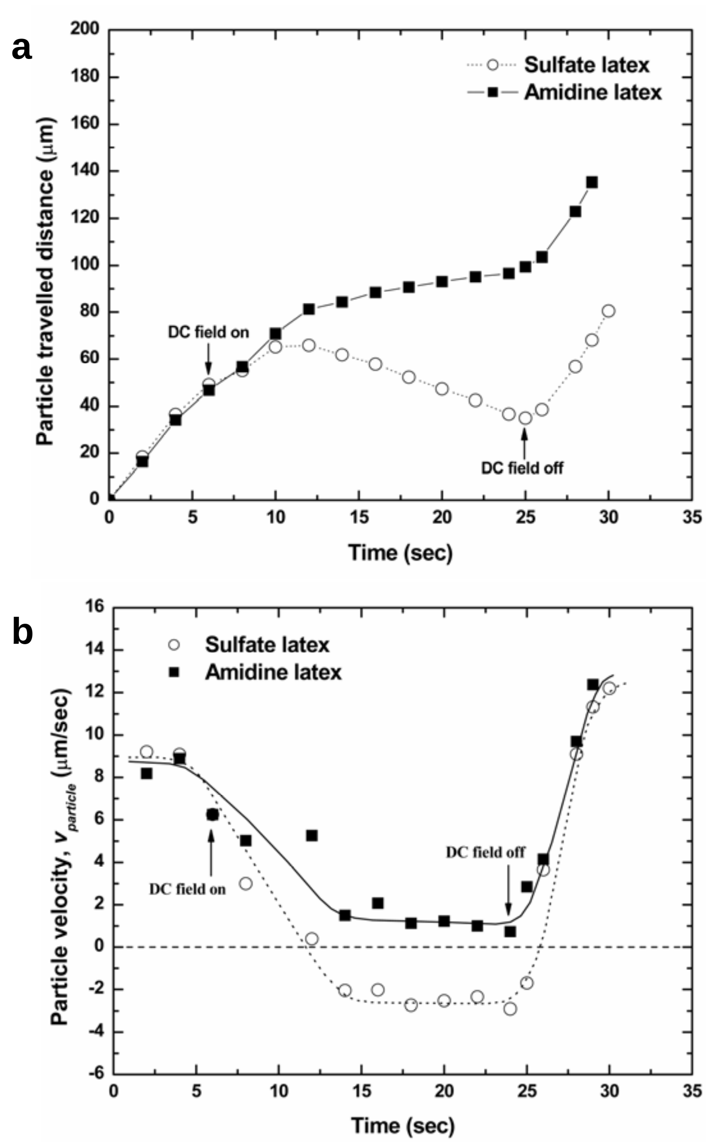
Supplementary Figure S3. Diode velocity changes little with the concentration of non-adsorbing electrolytes. Experiment was performed at E_{ext} = 93 V/cm and frequency 1 kHz.



Supplementary Figure S4. Positions of two photodiodes propelling across the same vessel - when either of them is illuminated with a strong beam of light it begins moving slower. Experiments were performed at E_{ext} = 100 V/cm, 10^{-6} M NaCl, and 1 kHz. See also Supplementary Movie M6.



Supplementary Figure S5. The diodes can also propel in non-aqueous media. Diode velocity in organic solvents is lower than on water due to high viscosity and lower surface charge. Experiments were performed at frequency 1 kHz.



Supplementary Figure S6. Mobility of two particles of slightly different charge measured in terms of (**a**) particle position and (**b**) particle velocity. The particles begin moving together when the liquid is moved by AC pumping at 40 V only. The application of DC field of 4V introduces an electrophoretic component of the motion in a direction opposite to the one of the AC pumped flow. The sulfate latex particle begins moving faster than the fluid, while the amidine latex moves a slower than the surrounding fluid. The particles begin moving in opposite direction and the distance between them increases with time. Compare with Figure 5 and Supplementary Movie M6. Similar processes with precisely adjusted AC+DC counterflows could be used in efficient separations of cell cultures and proteins of similar charges.

Parametric comparison - published AC electrohydrodynamic pumps and diode pumps reported in this manuscript

Authors / year	Channel dimension (μm)	electrode gap (μm)	Length of periodic electrode pattern (mm)	u_{max} (μm/sec)	Operating voltage (V)	Operating Frequency (kHz)	**Electric field (V/cm)**	**Q_{max} (μL/sec)**
Brown et al. (2000) [1]	H 340 (laterally open channel)	4.5	6.5	120	1.2 Vrms	~ 0.8	**2667**	**-**
Studer et al. (2002)	W 50 × H 20	3	-	40	1.5 V	5	**5000**	**$9.6{\times}10^{-7}$**
Mpholo et al. (2003) [2]	H 280 (laterally open channel)	2	5.28	450	2.2 Vrms	14 ~ 17	**11000**	**-**
Debesset et al. (2004) [4]	W 100 × H 100 (loop channel)	5	28.19	50	1.8 Vrms	5	**3600**	**0.0005**
Studer et al. (2004) [5]	W 100 × H 20 (loop channel)	8.7	6	500	8 Vrms	32 (flow direction depends on frequency)	**9195**	**0.001**
Bazant & Ben (2006) [6] **Theoretical prediction**	W 500 × H 100	5	-	190	1 Vrms	10	**2000**	**0.009**
Diode pumps in this manuscript	W 300 × H 570 (square loop)	2 cm (2 electrodes)	1 mm (diode length)	40	160 Vpp	0.1-40 Independent	**80**	**0.003**

[1] Brown, ABD; Smith, CG; Rennie, AR; Pumping of water with ac electric fields applied to asymmetric pairs of microelectrodes, *Phys. Rev. E* (2000) 63, 016305.
[2] Studer, V; Pepin, A; Chen, Y; Ajdari, A; Fabrication of microfluidic devices for AC electrokinetic fluid pumping, *Microelectronic Eng.* (2002) 61-62, 915-920.
[3] Mpholo, M; Smith, CG; Brown, ABD; Low voltage plug flow pumping using anisotropic electrode arrays, *Sensors Actuators B* (2003) 92, 262-268.
[4] Debesset, S; Hayden, CJ; Dalton, C; Eijkel, JCT; Manz, A; An AC electroosmotic micropump for circular chromatographic applications, *Lab Chip* (2004) 4, 396-400.
[5] Studer, V; Pepin, A; Chen, Y; Ajdari, A; An integrated AC electrokinetic pump in a microfluidic loop for fast and tunable flow control, *Analyst* (2004) 129, 944-949.
[6] Bazant, MZ & Ben, Y; Theoretical prediction of fast 3D AC electro-osmotic pumps, *Lab Chip* (2006) 6, 1455-1461.

Additional experimental details

Diode types used and dimensions: Silicon switching microdiodes for surface mounting (1.1 mm × 0.7 mm × 0.5 mm, Part no. 1N4448HWTDICT-ND, Digi-key Co.), Silicon switching diodes (3.7 mm × Ø 1.8 mm, Radioshack), Surface mount light emitting diode (1.0 mm × 0.45 mm × 0.45 mm, Part no. JRC0168, IDEA, Inc.), Light emitting diodes (Ø 3.0 mm, Radioshack), Silicon photodiodes (2.25 mm × 2.25 mm × 2.75 mm, Part no. PDB-C144, Photonic Detectors Inc.), Zener diodes with reverse voltage 6V (1.2 mm × 0.6 mm × 0.6 mm, Part no. MAZS0620MLCT-ND, Digi-key Co.), Zener diodes with reverse voltage 12V (1.2 mm × 0.6 mm × 0.6 mm, Part no. MAZS1200MLCT-ND, Digi-key Co.).