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Citation: Applied Physics Letters **98**, 153512 (2011); doi: 10.1063/1.3580760
View online: http://dx.doi.org/10.1063/1.3580760
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/98/15?ver=pdfcov
Published by the AIP Publishing

Light-driven manipulation of picobubbles on a titanium oxide phthalocyanine-based optoelectronic chip

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(Received 30 July 2010; accepted 23 March 2011; published online 14 April 2011)

Microbubbles have a variety of applications in science and biological technology. Here, we demonstrate the manipulation of the picoliter gas bubble (picobubble) based on the optoelectronic-mechanism. The organic photoconductive material, titanium oxide phthalocyanine (TiOPc), was developed to make the light-sensitive substrate of this optoelectronic chip. The virtual electrodes are formed by projecting the dynamic light pattern onto TiOPc layer for generating the desired nonuniform electric field. The picobubble suspended in silicone oil can be manipulated with the velocity of 40–50 μm/s. The driving force up to 160 pico-Newtons could be generated for manipulating a gas bubble of 300 picoliters. © *2011 American Institute of Physics*.
[doi:10.1063/1.3580760]

Recent research has reported considerable applications for microbubbles by utilizing various approaches. For example, ultrasound irradiation was applied to vibrate and destroy microbubble.[1,2] Utilizing the microbubble to perturb the cell membrane and the vessel wall to increase the permeability and interstitial delivery for targeted drug,[3] siRNA (Ref. 4) and therapeutic gene.[5] Other microbubble applications in microfluidics, for instance, are acoustic micromixer[6] and liquid micropump.[7] Recently several approaches focus on generating microbubbles by utilizing microfluidic device,[3] flow-rate controlled breakup,[8] geometrically mediated breakup,[9] and electrolysis.[10]

Electrowetting-on-dielectric actuation[11] and thermocapillary force[12] are reported for the manipulation of microbubbles. Dielectrophoresis (DEP) phenomenon has been also developed to manipulate polymer beads,[13] cells,[14] and bubble.[10,15,16] Besides, the optical image-driven DEP technique named as optoelectronic tweezers (OETs) has been invented and applied for manipulating microparticles,[17] cells,[18,19] and DNA.[20] In this letter, we demonstrate the optoelectronic approach to manipulate the hollow-volume gas picobubble suspended in oil liquid on a titanium oxide phthalocyanine (TiOPc)-based substrate. We utilize light-induced optoelectronic driving force to manipulate the bubble which has the volume less than 300 pl. The picobubble can be optically driven within the view region, 1 mm$\times$1 mm, on the TiOPc-based optoelectronic (Ti-OET) chip.

Figure 1 illustrates the experimental setup for the required optical system to manipulate the picobubbles on our TiOPc-based optoelectronic chip. The light source is a Philips UHP mercury lamp and concentrated through a lens, L. A multitouch panel (MSI, AE2220) is used to control the image on a digital micromirror display (DMD, 1024$\times$768 pixels). A real-time user interface is programmed by using the built-in actionscript function of the FLASH software (Adobe Systems Co., Ltd.) for convenient and intuitive control. Through a pair of focusing lenses, L1 (with a 200 mm focal length) and L2 (with a 10 mm focal length), the light pattern shrinks to 1/20 the original light pattern size to fit the working area on the chip. The light pattern is projected onto the TiOPc-coated substrate as the light is reflected from the DMD. The charge coupled device is used to record all the manipulation process of the picobubble.

The organic photoconductive material[21] comprising phthalocyanine pigments (TiOPc), which have the similar photoconductive characteristics like a-Si (Refs. 17 and 18) and bulk-heterojunction polymers,[22] has been widely used as an electrophotographic sensitive member in the laser printer. There is only single process needed for fabricating the photoconductive substrate of our TiOPc-based chip, which is much simpler than former reports.[17,18,22] A thin TiOPc layer of about 200 nm is spin-coated at 1500 rpm for 20 s on the ITO glass. After baking at 130 °C for 30 min, the material property of TiOPc substrate stays stable for at least four months under normal operation. Our Ti-OET chip, as illustrated in Fig. 1, consists of sandwiched layer of top transparent ITO electrode, silicone oil (Dow Corning 200® fluid, 5cSt) and a thin TiOPc layer on the bottom ITO glass sub-

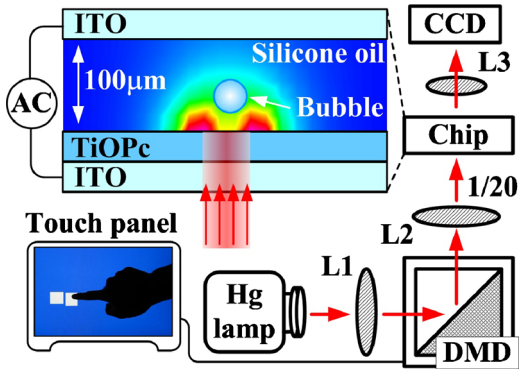

FIG. 1. (Color online) Schematic diagram of the optical system setup for our touch-panel-based light-driven optoelectronic-mechanism chip. The light-induced electric field generates appropriate force to trap the picobubble suspended in silicone oil toward the illuminating area.

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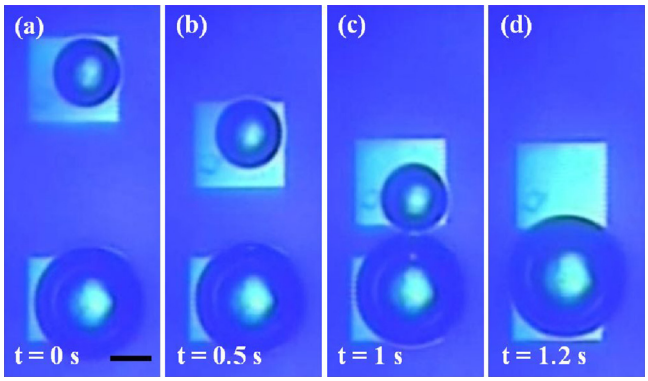

FIG. 2. (Color online) The bubble is dragged by following the trajectory of the moving light square. The light-induced driving force drags a 50 pl volume bubble to fuse another 220 pl bubble. The scale bar is 30 μm. (enhanced online, bubbles_manipulation.mov). [URL: http://dx.doi.org/10.1063/1.3580760.1]

strate. The picobubbles are generated by placing 1 cc Eppendorf containing 500 μl silicone oil on the vibrator (Scientific Industries, Inc., vortex genie 2) for 5 min. After vibrating, the 50 μl silicone oil embedded with bubble is loaded into the Ti-OET chip.

A commercial finite element software CFD-ACE+ (CFDRC, Huntsville, AL) is utilized to simulate the steady-state electric field, which dominates the light-induced optoelectronic-mechanism force.[19] Figure 1 also shows the simulation results for the root mean square of ac electric field (E_square). The red color near the edge of the illuminating area represents the stronger ac electric field. The blue color region far away from the illuminating zone represents the weaker ac electric field. The light-induced driving force attracts the picobubble toward the light pattern.

The TiOPc has good light-sensitive electrophotographic characteristics from green to infrared region.[23] The illuminating white light, which contains green and red light, decreases the impedance of TiOPc; but the blue light almost has no influence on this photoconductive substrate. In this research, we use white-color light pattern to manipulate bubbles and blue-color background for the observation. While the square white-light pattern shown in Fig. 2 is projected to the TiOPc surface, the induced virtual electrode forms on the illuminating region. A nonuniform electric field is, then, generated between the top ITO glass and the bottom TiOPc surface. This electric field distribution results in the optoelectronically driven force to drive the picobubble toward the illuminating region when the 10 Vpp ac voltage in the frequency range of 1 Hz to 20 MHz is applied to our TiOPc-based optoelectronic chip. When a finger drags the white square on the touch panel, the trapping square projected onto the TiOPc surface simultaneously moves the picobubble. The ac voltage of 10 Vpp at 10 kHz is applied between the top and button ITO glass to trap the picobubbles suspended in the silicone oil. Figures 2(a)–2(d) demonstrates the bubble-fusion process utilizing the light pattern to manipulate two bubbles, 50 pl and 220 pl. The light-induced driving force drags the picobubbles to follow the trajectory of the moving light square.

Figure 3 demonstrates the feature of utilizing the trapped picobubble to indirectly drive single polymer bead. In Fig. 3(a), the light-induced driving force traps a 185 pl picobubble within the square light pattern. The black and the red arrows highlight the position of the two 15 μm diameter

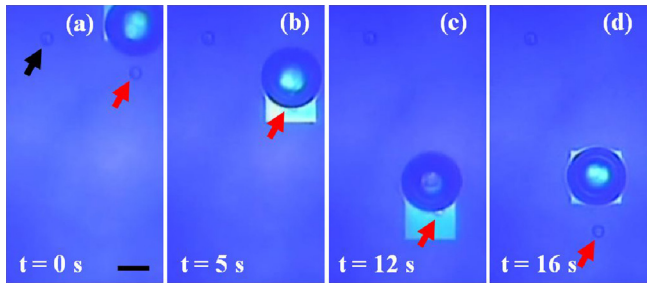

FIG. 3. (Color online) A 15 μm diameter bead indicated with the arrow is manipulated via the optically driven picobubble. The scale bar is 35 μm. (enhanced online, bead_manip_via_picobubble_tweezer.mov). [URL: http://dx.doi.org/10.1063/1.3580760.2]

polymer beads. When an ac voltage of 10 Vpp at 10 kHz is applied to our chip, the light-induced driving force has no influence on the polymer beads. However, the light-induced optoelectronic driving force would drive the picobubble on this condition. In Figs. 3(b) and 3(c), the light-induced optoelectronic-mechanism force drives the picobubble to push the 15 μm bead downwards. Comparing the bead position indicated by the red arrow in Figs. 3(a) and 3(d), the bead is driven 185 μm in this demonstration.

When the picobubble is driven with a constant velocity on the Ti-OET chip, the driving force resulting from the light-induced optoelectronic-mechanism equals to the viscous drag.[22,24] An indirect approach to estimate the light-induced driving force is based on Stokes' law, i.e., $F_{\text{Ti-OET}} = 6\pi r \eta v_{\text{Ti-OET}}$.[18] Here, η is the medium viscosity and $v_{\text{Ti-OET}}$ is the steady-state velocity of the picobubble. Figure 4 characterizes the light-induced driving force acting on the picobubble. When a gas bubble suspended in the liquid, two factors dominate the bubble volume. One is the concentration of dissolved gas in the liquid and the other is the surface tension of the gas bubble-liquid interface. As the bubble radius decreases, the surface tension increases. The air molecules are then brought to diffuse into the surrounding liquid until the bubble vanishes.[25–27] Before the bubble disappears, the light-induced driving force can still manipulates its position by moving the light pattern. The gas molecules inside the picobubble dissolve slowly into the silicone oil during the manipulation process. The maximum light-induced driving force is 160 pN as it drives a 300 pl picobubble. As the bubble volume decreases to less than 100 pl, the light-induced driving force is reduced rapidly. The minimum measurable light-induced driving force is about 30 pN acting on

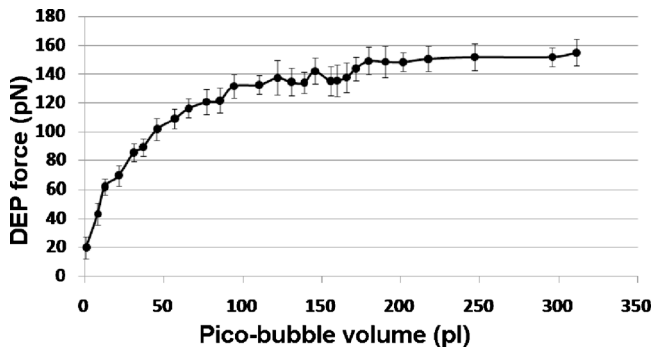

FIG. 4. (Color online) The relationship between light-induced driving force and picobubble volume. The ac voltage of 10 Vpp at 10 k Hz is applied between the top and button ITO glass.

a 4 pl picobubble with a steady-state velocity of 35 μm/s.

The effects of electrothermal flow,[12] buoyancy,[28] light-induced ac electroosmosis,[29] and light-induced DEP (Refs. 17–19) contribute to the dynamics of light-driven particles in the OET device.[28] In our TiOPc-based optoelectronic chip, the organic material TiOPc has good absorption property at 700–800 nm.[30] The power density of our light source, a UHP mercury lamp, projected onto the TiOPc layer is characterized as 0.33 mW/cm^2 by using a power meter, Ophir NOVA II. This power energy is too weak to generate enough temperature gradient for obvious electrothermal flow and buoyancy effects on our TiOPc-based optoelectronic chip. The ac electroosmosis induced flow velocity is frequency dependent.[31] However, the velocity of our light-driven picobubble is characterized as 40–50 μm/s for the bubble volume of 50–200 pl at the operational frequency varying from 1 Hz to 20 MHz. Based on our experimental characterization, we did not observe the frequency dependence of the light-induced velocity for the bubble manipulation on our TiOPc-based optoelectronic chip. From the viewpoint of DEP principle, the bubble is always trapped and dragged within the illuminating region. When the ac voltage is turned off, the movement of the square light pattern has no influence on the bubble. When the ac voltage is on, the bubble can be driven to follow the path of the light pattern which is the maximum electric field region.[19,24] Thus, most other candidates of driving mechanisms can be ruled out by our controlled experiments. DEP could be the most likely driving mechanism for the light-driven manipulation of picobubbles on our TiOPc-based optoelectronic chip. This bubble manipulation process is in agreement with the positive DEP phenomenon reported in the article of OETs.[17] However, the DEP theory might predict that the bubble suspended in silicone oil is experienced the negative DEP force.[15] Although the light-induced DEP manipulation of the picobubbles suspended in silicone oil under the nonuniform electric field is the most likely mechanism, a full investigation would be needed to confirm the driving mechanism.

The time span of a picobubble being manipulated till it vanishes is about 10 min. The phenomenon has been studied based on Henry's law.[26,27,32] When the gas concentration of silicone oil is saturated, the picobubble vanishes more slowly and lasts longer for manipulation. This approach can provide a suitable method to fuse two and more different gas bubbles. Furthermore, the experimental results reveal the induced charges assembling on the gas-oil interface. For example, two approaching bubbles are attracted slightly to each other. However, there is very limited study on these electrodynamic phenomena which are the process of induced charge generation, distribution and diminishing between the gas-liquid interfaces. Utilizing this dynamic manipulation approach for picobubbles might offer an opportunity to clarify the basic physics phenomena.

In conclusion, this research utilizes light-induced driving force to manipulate the gas picobubble on the Ti-OET chip fabricated by using the photoconductive material, TiOPc. The touch panel is integrated into the optical system to make the bubble control convenient and intuitive. The light-driven picobubble is demonstrated to push a 15 μm bead. This work also characterizes the relationship of light-induced driving force and picobubble volume. The bubble manipulation technique provides a potential for various picobubble applications.

The authors would like to thank the National Science Council of Taiwan (Grant No. 98-2120-M-007-003) for the financial support. The corresponding author thanks Professor Pei-Yu Chiou, Professor Ming C. Wu, and Professor Gwo-Bin Lee for sharing OET experience and helpful discussion. Dr. Ming-Huei Liu (Sinonar Corp., Taiwan, R.O.C.) provides TiOPc and the technical discussion.

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