Various Microbubbles Generation by Light Excited Graphene Oxide Heater

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Abstract— Microbubbles have stimulated broad attention for the highly-efficient contrast agents in biomedicine and microfluidic control. We present an optical technique to produce various kinds of microbubbles, using a near-infrared light exciting photothermal graphene oxide deposited on a microwire. As a heater, GO-deposition can absorb the evanescent field to produce heat energy, and then heat the solvent to create photothermal microbubbles. It can also translate the optical energy into the ultrasonic energy and compress the solvent to create cavitating microbubbles. Furthermore, a series of approximately ellipsoidal microbubbles can be generated on a smooth microwire due to heterogeneous nucleation.

1. INTRODUCTION

Recent reports have shown the growing attention of microbubbles in a wide variety of fields, particularly in the biomedical engineering [1], microelectromechanical systems (MEMS) [2], and lab-on-a-chip technology [3–5]. For example, the monodisperse microbubbles have been demonstrated to be the highly-efficient contrast agents in medical imaging [1]. Microbubble powered actuator has been extensively applied in mixers [3], switches [4], valves [5] and pumps [5] in microfluidic chip. And there is also a growing interest in using convection flow induced by vapor microbubble for particles manipulation. Accordingly, the generation of microbubbles in fluids has attracted increasing attention. Numerous techniques including flow-focusing devices [6], T-junction devices [7] and ultrasound-induced cavitation [8] have been proposed. However, there is still a challenge to generate different kinds of microbubbles by single device.

The techniques based on optically controlled systems have been adopted to generate a variety of microbubbles. Previous reports show that single microbubble can be generated and controlled accurately based on photothermal effect, by using highly focused laser beams to illuminate optically absorbent substrates [9] and absorbing liquids [10]. And the laser can also induce cavitation to obtain massive microbubbles [11]. However, the natural dependency to the illuminating laser in free space will cause external optical energy leaking outside, and require complex focus systems and high laser intensity.

Recently, micro/nanowire has been demonstrated to exhibit much tight field confinement and strong evanescent field [12]. So in view of cost and operability, it is inferred that assembling photothermal materials onto microwire can be more desirable to generate multiple microbubbles. Graphene oxide (GO), the electronically hybrid material possessing excellent nonlinear absorption and nonlinear scattering properties, enables the potential applications in saturable absorbers, optical switching and optical limiter [13]. The present study develops a novel device by depositing GO nanosheets (GONs) onto a microwire. Excited by the near-infrared light, GO-deposition can act as a heater for creating variety of microbubbles. According to the mechanism of photothermal effect, heterogeneous nucleation, and cavitation, vapor microbubbles, ellipsoidal microbubbles, and cavitating microbubbles can be respectively generated.

2. DEVICE FABRICATION

Here GONs was prepared by oxidizing natural graphite powder based on a modified Hummers method [14, 15]. And the GONs suspension was prepared by mixing GONs with N,N-dimethylformamide (DMF) solvent and several hours of 240 mW ultraphonic treatment was required for efficient

exfoliation and dispersion into DMF solvent. The transmission electron microscopy (TEM) image, observed by using a JEOL JEM-2100F transmission electron microscope shows the morphologies of flake-like reduced GONs (Figure 1(a)). To demonstrate the absorption property of GONs, the absorption spectra of GONs suspensions in different concentration were studied and shown in Figure 1(b). It can be seen clearly that pure DMF has a low absorption in the operating wavelength of 1525–1565 nm (see black line in Figure 1(b)). And the absorption of the GONs suspensions increase as GONs concentration increases.

Figure 2(a) schematically shows the experimental setup for the fabrication of GO-heater and microbubbles generation. A microwire (diameter: 0.5–5 μm) was controlled by a microadjuster with one end connected to an optical source and the other placed in a microfluidic chamber, which is fabricated by drawing a single mode optical fiber (SMF-28, Corning Inc.) through the flame-heated technique [12]. The optical source was provided by an amplified spontaneous emission broadband light source (ASE, ∼10 mW, 1525–1565 nm) connected with an erbium-doped fiber amplifier (EDFA), whose output power can be tuned from 10 mW to 400 mW. And we also use an inverted microscope with a charge coupled device (CCD) camera for observation, image capture, and video recording.

After the GONs suspension was introduced to the microfluidic chamber and the light was injected into the microwire, the leaking light energy was absorbed by the GONs in the zone of evanescent field. And then a weak convective flow was generated, driving the adjacent GONs to swim into the evanescent field and finally deposit on the microwire [16, 17]. The process of the deposition would go on until the laser was turned off, as shown in Figures 2(b)–(c). Figure 2(c) shows a typical SEM image of a GO-deposition. It can be seen that even though turning the light off the deposition remained attaching to the surface of the microwire due to van der Waals forces. Under the excitation of near-infrared light, the enhanced optical absorption could give rise to the increasing heat energy on the GO-deposition, which can be also served as a microheater. And we also used the GO-heater to generate various microbubbles, including photothermal microbubbles, ellipsoidal microbubbles, and cavitating microbubbles.

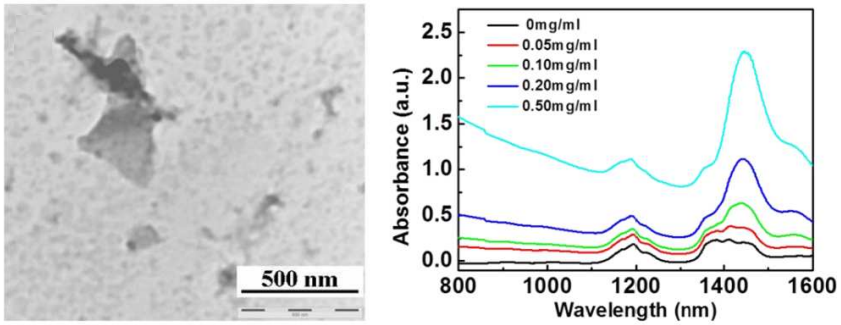

Figure 1: (a) TEM image of GONs shows a scale-like structure. (b) Absorption spectra of GONs dispersions in DMF at the concentration of 0, 0.05, 0.10, 0.20, 0.50 mg/ml, at wavelength of 800–1600 nm.

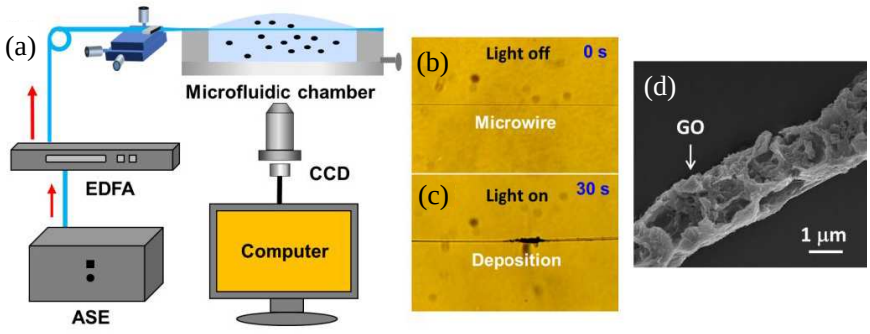

Figure 2: (a) Schematic of experimental setup. (b) Microscope images of microwire. Scale bar: 50 μm. (c) Microscope images of the fabrication process after the laser was launched. Scale bar: 50 μm. (d) A typical SEM image of a GO-heater.

3. GENERATION OF PHOTOTHERMAL MICROBUBBLES

Based on boiling effect, the working GO-heater was capable of initiating the phase transition of surrounding solvent (such as DMF) to generate photothermal microbubbles [18]. To demonstrate the growth dynamic of these microbubbles, experimentally we first used a punctiform GO-heater on a microwire tip to generate single microbubble. Figure 3(a) shows the microbubble generation under the exciting power of 10 mW. The microbubble was formed and kept on growing until reaching its maximum size. After it was explored, a new microbubble was formed and repeated the growing process (see optical images in Figure 3(a)). Each microbubble would experiment similar growth tendency, with a relatively rapid growth and an approximately constant speed growth (see the growth curve in Figure 3(a)). Further observation shows the growth was faster and the maximum diameter was larger for the higher optical power. This was contributed to higher optical absorptions and larger temperature increase.

The punctiform GO-heater can generate single microbubble with controllable size, but suffer deficiency in producing multiple microbubbles due to the small-area heating. By amplifying the area, we also point out that a great quantity of thermal microbubbles can be produced on line-shaped GO-heater with length of 155 µm. Under the exciting power of 40 mW, each microbubble was stationary and grew continuously to reach a certain diameter, and following it would detach from the GO-heater and float in the liquid suspensions (see optical images in Figure 3(b)). During a period of 6 min, 113 detaching microbubbles were recorded, where the diameter concentrated in 60–140 µm (see the statistic histogram in Figure 3(b)).

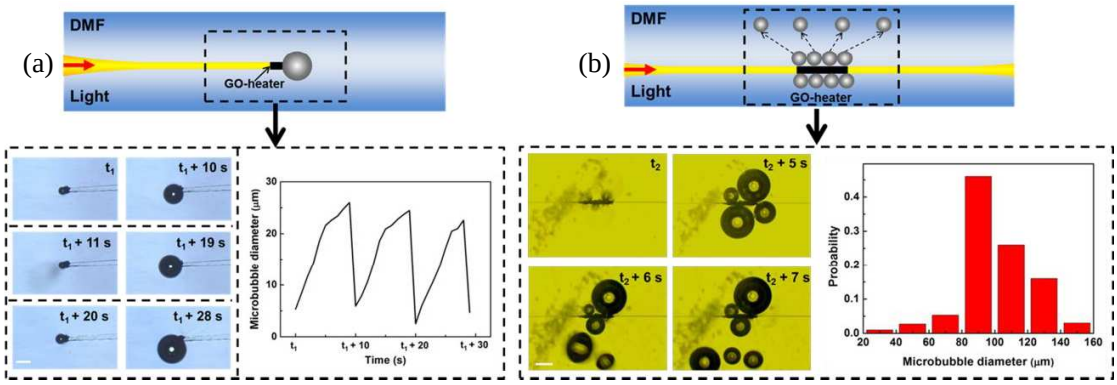

Figure 3: (a) Schematic and experimental results for the photothermal microbubbles generated on a punctiform GO-heater. Scale bar: 15 µm. (b) Schematic and experimental results for the photothermal microbubbles generated on a line-shaped GO-heater with length of 155 µm. Scale bar: 50 µm.

4. GENERATION OF ELLIPSOIDAL MICROBUBBLES

Through the microadjusters, a new GO-heater formed on the microwire was tuned to be located at the DMF/air interface and its right microwire segment was immersed in the DMF solvent (see Figure 4). Under the exciting power of 40 mW, it was difficult to form microbubbles on the GO-heater. Instead, there were abundant DMF vapors in the liquid by the GO-heater and the immersed microwire could provide preferential sites to facilitate nucleation based on heterogeneous nucleation [19, 20]. Finally, a series of microbubbles were generated and grew along a horizontal microwire axis. Each microbubble exhibited a symmetrical conformation with respect to the microwire axis and took a shape of ellipsoid (see Figure 4). The microbubble behaviours were linked closely with the temperature field. Several microbubbles were observed to continuously move towards the GO-heater or coalesce together. We contributed the driving force of directional transport to thermocapillary effect [19, 21] or non-equilibrium Laplace pressure along the microbubble [19, 22]. The existence of novel type of microbubble will gain new insight into the mechanism of bubble formation and bubble dynamics.

5. GENERATION OF CAVITATING MICROBUBBLES

In addition to boiling and heterogeneous nucleation, cavitation (the phenomena of the expansion of bubble nuclei by a fast lowering of the liquid pressure) is also the main method for microbubble generation. Previously, cavitation could be triggered spontaneously in the microcavities under the

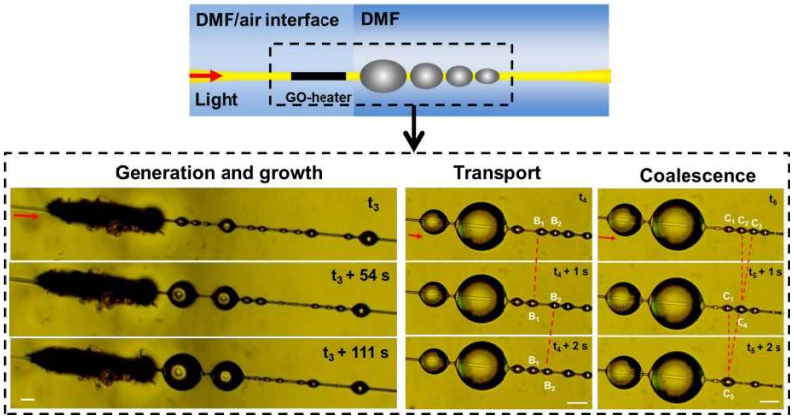

Figure 4: Schematic and experimental results for the ellipsoidal microbubbles generated on a microwire. Microbubbles were observed to continuously move towards the GO-heater or coalesce together. Scale bar: 25 μm.

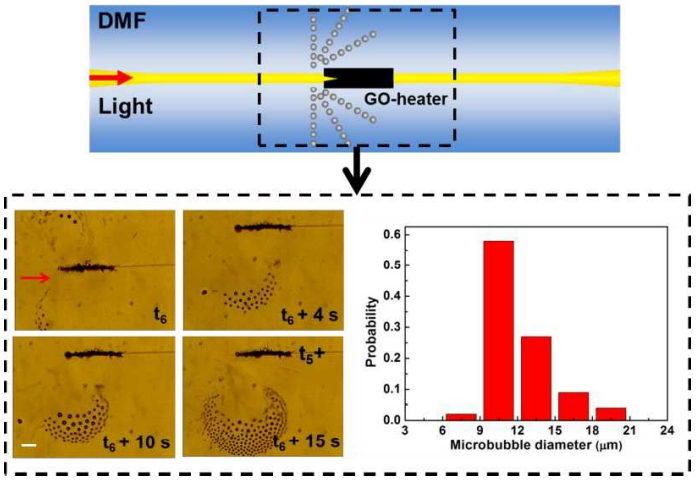

Figure 5: Schematic and experimental results for the monodisperse microbubbles generation from cavitation. Scale bar: 20 μm.

action of ultrasound [8]. In the experiment, we used the light with power at 40 mW to excite a GO-heater with the surface patterned with microcavities. Unlike the photothermal microbubbles generated directly on the GO-heater, there were massive microbubbles being immersed near the microcavity and ejected away. As shown in Figure 3, there were about 254 cavitating microbubbles being generated at the time of $t_6 + 15$ s. And the statistic histogram of the size distribution in Figure 5 also shows microbubbles with monodisperse state and the main diameter at 9–15 μm, demonstrating the smaller size than photothermal microbubbles in Figure 3. We speculated that the pressure wave was created by the light, traveled over the heater and focused on the microcavity. Thereby it can quench liquid instantly to negative pressure, leading to liquid cavitation and eject large amount of microbubbles.

6. CONCLUSION

In conclusion, we have demonstrated a simple and effective method for generating various microbubbles by depositing GO on a microwire. GO can heavily absorbed evanescent field and release strong heat under the excitation of infrared light, which can heat surrounding liquid. Three kinds of microbubble were successfully generated by the GO-heater. Firstly, at the low excitation power the superheat limit of the liquid can be reached to generate thermal microbubbles. Secondly, a series of ellipsoidal microbubbles can be formed and grew symmetrically along the microwire axis based on heterogeneous nucleation when the heater is located at liquid/air interface. Finally, massive cavitating microbubbles can be immersed near a GO microcavity and ejected away. This technique has prospective applications in optofluidic control, microfluidics, microbubble-based devices, and

other biochip techniques.

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