Optimization substrates and implantation metals for high performance photoacoustic laser streaming

Xin Ai* and Yunao Qiu
Institute of Fundamental and Frontier Sciences, University of Electronic Science and Technology of China, Chengdu 610054, Sichuan, China

*Corresponding author. Email: Alexai0126@163.com

Abstract Optical manipulation of fluid has been widely investigated for applications in microfluidics, and photoacoustic laser streaming provides a promising technique because of its strong driving ability and flexibility as a microfluidic pump. However, except for the gold and quartz, other substrates and metals have never been investigated in the fabrication of laser streaming pump. In this work, we demonstrate the effect of substrate and metal types on the performance of laser streaming. The Au-implanted quartz pump exhibit higher initial flow speed than Fe, while the durability of Fe-implanted plate is longer. The quartz substrate has a similar initial flow speed to glass, but much better endurance under long-time laser irradiation. In addition, the flow speed of incident laser with gradually increased power will be much higher than the direct high laser power. This study demonstrates the effective laser streaming of different substrates and implantation metals, thus paves the ways for optimizing the performance of photoacoustic streaming pump.

1. Introduction
Controlling or driving the fluid efficiently and accurately has been a research hotspot in the last decade. Light control of liquid droplet and thin liquid surface have intrigued enormous scientists because of its contactless, precise and temporal spatial liquid actuation in applications such as microfluidics, physical dewetting and welding, chemical microreactors and bioscience system [1-3]. In the current, the most used methods include optical pressure, optoelectrowetting, thermocapillary effect (Marangoni effect), and photophoresis, which can only achieve a flow speed of millimeters per second. The optical radiation driving is limited in nano-micrometer scale as the photon momentum is very weak, while optoelectrical actuation is also restricted to conductive liquid [4]. Optocapillary effect (Marangoni effect) uses the surface temperature difference to manipulate the droplets, but it is only suitable for temperature-sensitive liquid [5-9]. In 2017, it was discovered that the nanosecond pulse laser can drive macroscopic laser streaming in cuvette filled with gold nanoparticles, and the flow velocity reached the level of 4 cm/s [10]. Subsequently, the microfluidic pump fabricated by gold ion implantation on quartz plate achieved real-time control of the flow field, making it more prospective in microfluidic area [11]. However, the effect of other implantation metals and substrates on laser streaming remains unknown. In order to further improve the driving ability and durability of photoacoustic streaming pump, the fabrication parameters need to be systematically optimized.

In this work, we investigated the effect of substrate types and thickness, implantation metals and dose on the flow velocity and endurance of laser streaming pump. This study provides alternative
approaches for optimize the performance of photoacoustic streaming and promotes its practical applications.

2. Result and discussion
The experimental setup is shown in figure 1. A 532-nm pulsed laser (150-ns pulse width) was focused (5-cm focal length lens) on the front surface of the plate, which was implanted by metal ion under 50 kV acceleration voltage. The cell was filled with polystyrene fluorescent microspheres water solution (Catalog no:7-1-0300, Maximum emission wavelength: 680 nm, Particle size: 3 μm; Tianjin Junyijia Technology Co., Ltd.), and was illuminate the field of view by 632.8 nm He-Ne laser through the cylindrical lens. The high-speed camera (Catalog no: FT-U3F500, Shenzhen Fangte Technology Co., Ltd.) was set in the side of the cell to capture the motion of laser streaming, and the black dotted frame represents the area captured by the camera. There is a 532 nm long-pass filter in front of the camera to block the incident pulsed laser for flow imaging. An attenuator is placed behind the pulsed laser to control the power.

2.1 Experimental setup
(a) Schematic of experimental setup. (b) The absorption spectrum of the Fe- (2×10\(^{17}\) per cm square) and Au- (5×10\(^{16}\) per cm square) implanted quartz plate. (c) The flow speed of Au- and Fe-implanted plates in 30 mins. (d) Maximum flow speed of Fe-implanted quartz plate. (e) Maximum flow speed of Au-implanted quartz plate.

![Figure 1](image_url)

Figure 1 (a) Schematic of experimental setup. (b) The absorption spectrum of the Fe- (2×10\(^{17}\) per cm square) and Au- (5×10\(^{16}\) per cm square) implanted quartz plate. (c) The flow speed of Au- and Fe-implanted plates in 30 mins. (d) Maximum flow speed of Fe-implanted quartz plate. (e) Maximum flow speed of Au-implanted quartz plate.

In our previous work, laser was used to irradiate nanogold solution or gold ion implanted quartz substrate to generate ultrasonic driving fluid\(^{[11,12]}\). Unlike previous study, we used Fe as the implanted ion instead of gold to design the best performance device and analyze its mechanism. Figure 1(b) exhibits the transmission spectrum of Fe-implanted and Au-implanted quartz. It is obviously that gold has strong absorption around 532 nm, in order to compared the speed and durability of the two type of metal, we increased the concentration of iron to a dose of 2×10\(^{17}\)/cm\(^2\), which is as much as 4 times than...
that of gold. According to our demonstration, Au-implanted plate can generate a directional long-lasting ultrasound wave which drives the fluid via acoustic streaming. The same phenomenon was also found in the Fe-implanted quartz plate. Figure 1(c)-(e) show the change of speed after half an hour, and maximum speed for two micropumps under 20 mw. It can be observed that the gold has higher driving flow speed than iron, but Fe shows more long-lasting lifetime under long-time laser irradiation. We assume the reason of different flow speed may be related to the coefficient of thermal expansion (14.2×10^{-6}/K for Au and 12.2×10^{-6}/K for Fe respectively). The laser-induced heating and photothermal expansion of the Au-implanted plate induces a stronger vibration of plate and contacted liquid media than Fe, thus generating faster flow. Meanwhile, the higher melting point of Fe may contribute to the less decline of speed. This is probably because the bombardment of the pulsed laser caused the continuous melting and solidification of the substrate, and the embedded ions were continuously taken out of the surface.

As an important factor, a suitable substrate also plays an essential role in laser-driven device. Here we chose normal glass and quartz to study the damage and driving mechanism. Figure 2(a) shows the speed and lifetime of Fe-implanted quartz and glass under 50 mw. Glass-substrate showed a little faster speed than that of quartz in the beginning but decreased to a very weak level in few minutes. To illustrate this phenomenon, the optical images of the plates after 5 mins 50 mw laser irradiation were shown in figure 2(b)-(e). The transmission and reflection pictures both indicate that most of implanted materials are lost during laser illumination, but more iron particles remain on the glass substrate. We notice that the glass and quartz have the similar thermal conductivity (1 w/m.k and 1.46 w/m.k respectively), lower thermal conductivity plays an important role in the formation of local high temperatures, which is critical for faster jets. The difference in lifetime may be resulted from the different hardness. Therefore, choosing a harder and lower thermal conductivity material as the substrate is helpful to design a better performance micropumps.

**Figure 2** (a) Lifetime of two micropumps under 50 mw (Fe-implanted, 1×10^{17} per cm square). (b-c) Transmission image after 10 minutes of laser irradiation at 50mw of (b) glass and (c)quartz. (d-e) Reflection image after 10 minutes of laser irradiation at 50mw of (d) glass and (e)quartz.
Finally, our work also demonstrates how laser power influences the performance of the ultrasonic device. Figure 3(a) shows the relationship between speed and laser power. As the power increases, the speed of the ultrasonic device is also increasing. Interestingly, the lifetime of the micropumps does not seem to decrease. A gradient power increase is used in Figure 3(b): 10 mw for 20s, 30 mw for 50s to 50 mw. The results tell us that when using high power control devices, the preprocessing of the power gradient can achieve a faster speed.

3. Conclusion

In summary, we investigated the influence of substrates and implantation metals on photoacoustic laser streaming. The Au-implanted plate with high thermal expansion coefficient exhibits strong driving ability, while the Fe-implanted pump with high melting point metal shows longer durability. The implantation with lower cost, and broad band optical absorption provide more choice for optimization of ion implantation. In order to combine the advantages of implanted metals, composite materials implantation with both high thermal expansion, and strong light absorption may provide comprehensive merits for microfluidics[13-16]. Quartz substrate shows similar driving flow speed with glass but much higher durability because of laser-induced loss of implanted materials. Substrate with lower thermal conductivity and higher hardness may improve the robustness, but further study needs to be performed to reveal the mechanism. The coating of sol-gel precursor of SiO$_2$ to prepare thin film on implanted substrate or metal film may reduce the loss of particles and prolong the durability of the device[17-19]. This work demonstrated the effective laser streaming of different substrates and implantation metals, thus provides more approaches to optimize the photoacoustic pump, and paves the way for its practical applications.

References
[1] D. Baigl, Lab Chip 12, 12 (2012)
[2] S. Kou, C. Limmaneevichitr, Weld. J. 79, 5 (2000)
[3] J. P. Singer, S. E. Kooi, E. L. Thomas, J. Polym. Sci. Pol. Phys. 54, 54 (2016)
[4] A. Ashkin, J. M. Dziedzic, Phys. Rev. Lett. 30, 30 (1973)
[5] K. T. Kotz, K. A. Noble, G. W. Faris, Appl. Phys. Lett. 85, 85 (2004)
[6] C. N. Baroud, M. Robert de Saint Vincent, J.-P. Delville, Lab Chip 7, 7 (2007)
[7] E. Fradet, C. McDougall, P. Abbyad, R. Dangla, D. McGloin, C. N. Baroud, Lab Chip 11, 11 (2011)
[8] N. Kavokine, M. Anyfantakis, M. Morel, S. Rudiuk, T. Bickel, D. Baigl, Angew. Chem. Int. Edit. 55, 55 (2016)
[9] A. Diguet, H. Li, N. Queyriaux, Y. Chen, D. Baigl, Lab Chip 11, 11 (2011)
[10] Y. Wang, Q. Zhang, Z. Zhu, F. Lin, J. Deng, G. Ku, S. Dong, S. Song, M. K. Alam, D. Liu, Z. Wang, J. Bao, Sci. Adv. 3, 3 (2017)
[11] S. Yue, F. Lin, Q. Zhang, N. Epie, S. Dong, X. Shan, D. Liu, W.-K. Chu, Z. Wang, J. Bao, PNAS 116, 116 (2019)
[12] T. Buma, M. Spisar, M. O’Donnell, Appl. Phys. Lett. 79, 79 (2001)
[13] H. Won Baac, J. G. Ok, H. J. Park, T. Ling, S.-L. Chen, A. J. Hart, L. J. Guo, Appl. Phys. Lett. 97, 97 (2010)
[14] R. J. Colchester, C. A. Mosse, D. S. Bhachu, J. C. Bear, C. J. Carmalt, I. P. Parkin, B. E. Treeby, I. Papakonstantinou, A. E. Desjardins, Appl. Phys. Lett. 104, 104 (2014)
[15] S. Hwan Lee, M.-a. Park, J. J. Yoh, H. Song, E. Yun Jang, Y. Hyup Kim, S. Kang, Y. Seop Yoon, Appl. Phys. Lett. 101, 101 (2012)
[16] W.-Y. Chang, W. Huang, J. Kim, S. Li, X. Jiang, Appl. Phys. Lett. 107, 107 (2015)
[17] C. Yu, S. Zhu, D. Wei, F. Wang, Surf. Coat. Tech. 201, 201 (2007)
[18] W. Dou, P. Wang, D. Zhang, J. Yu, Mater. Lett. 167, 167 (2016)
[19] M. Epifani, C. Giannini, L. Tapfer, L. Vasanelli, J. Am. Ceram. Soc. 83, 83 (2000)