Scalable and Cost-Effective Nanowire Fabrication Using Ultrafast Laser with Optical 4f Laser Energy Modulation

Chong Chen[1,2,#], Jingwen Ran[1,2], Ziran Chen [1,2] and Xiaokang Liu [1,2]

1 Engineering Research Center of Mechanical Testing Technology and Equipment, Ministry of Education, Chongqing University of Technology, Chongqing 400054, China;
2 Chongqing Key Laboratory of Time-grating Sensing and Advanced Testing Technology, Chongqing University of Technology, Chongqing 400054, China;
Corresponding Author / Email: chongchen@cqut.edu.cn

KEYWORDS: Nanowires, Ultrafast laser processing, Optical 4f system, Laser energy modulation

Nanowires have always been a research hotspot due to their unique electrochemical, optical, and mechanical properties, particularly in their application as negative electrode materials for lithium-ion batteries. The traditional laser ablation method for preparing nanowires involves gas-phase growth by heating the target material to form high-temperature concentrated steam, which results in complex equipment and high costs. In light of this, this paper proposes a novel nanowire processing method by the use of an ultrafast laser with an optical 4f system for laser energy distribution modulation to directly process nanowires on the target material. A mathematical model is built to investigate the forming mechanism of single-pulse ablative surface profiles based on which the ablation model of nanowires has been established. Theoretical analysis and computer simulation have indicated that the proposed method might be a simple and cost-effective approach for large-scale, low-cost preparation of nanowires.

NOMENCLATURE

D = diameter
F_0= laser flux
F_{th}= ablation threshold fluence
w_0= focused laser beam spot radius on the focal plane
E_0= energy of a single peak pulse of the laser
h = ablated depth

1. Introduction

Nanowires are widely used in optoelectronics, microelectronics, plasma, and other fields for their unique electrochemical, optical, and mechanical properties, especially as anode materials for lithium-ion batteries [1-5]. The increasing demand for higher integration density, greater portability, and improved performance of modem devices calls for further improvements in pattern resolution and quality. Due to the limitations of the diffraction limit, conventional patterning techniques, such as electron beam, [6-9] focused ion beam, [10] X-ray [11], and deep ultraviolet laser beams, are employed to obtain high resolution. [12] Even if the resolution requirement is satisfied, the short wavelength beam suffers from the disadvantages of high operational costs, high vacuum requirements, complicated processes, low efficiency, and contamination of the substrate by processing chemicals. Because of these shortcomings, it is increasingly important to find a simple, economical, and efficient way to manufacture nanowires. Near-infrared femtosecond (fs) laser is a promising alternative to short-wavelength lasers, which can avoid the constraints of complex processes [13-16]. The traditional laser ablation method for preparing nanowires involves gas-phase growth by heating the target material to form high-temperature concentrated steam, which results in complex equipment and high costs[17]. In light of this, in this paper, a novel ultra-fast laser with a 4F optical system is proposed, which can process the nanowires on the target. This is a simple and cost-effective way to produce low-cost nanowires on a large scale.

2. Principle

2.1 Ultrafast laser ablation configuration

Fig.1 illustrates a schematic diagram of the prototype of the ultrafast laser ablation configuration. As illustrated in Fig. 1, a femtosecond laser having a central wavelength of 1040 nm (Spiritone 1040-8-SHG, Newport Spectra-Physics Technology Co., Ltd.), with an adjustable pulse width of 400 fs to 4 ps, and a maximum power of 8 W is used. A laser beam emitted from a laser source, in which an acoustic modulator

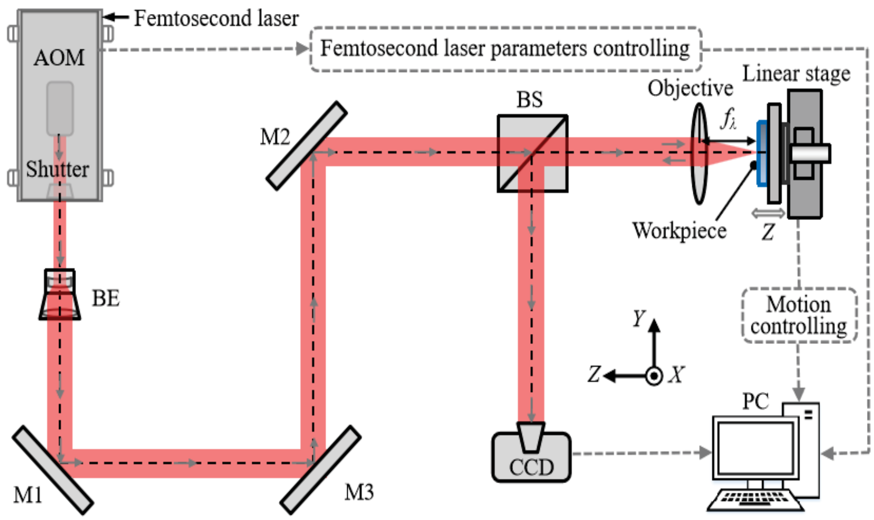

Fig.1. Schematic diagram of the prototype of the ultrafast laser ablation configuration.

(AOM) and a shutter which is assembled to control the opening/closing state of the laser source, is made to pass through a beam expander (BE). Three mirrors (M1, M2, and M3) are then used to bend the laser beam. The laser beam is focused on the surface to be ablated after passing through a non-polarized beam splitter (BS). The copper workpiece to be ablated was fixed on a three-axis linear motion stage with 50 nm positioning resolution per movement axis. An industrial CCD camera was used to monitor the ablation process.

2.2 Ultrafast laser ablation principle

Since the bimodal energy distribution of the femtosecond double hump laser beam is similar to Gaussian spatial distribution, the D^2 method [18] is used to separately calculate the spot diameter d of the laser beam focused on each ablative focal plane. According to the D^2 method, the relationship between the diameter D of the ablation position on the workpiece surface and the laser flux F_0 of the irradiation peak can be written as[19,20]

$$D^2 = 2w_0^2 \ln\left(\frac{F_0}{F_{th}}\right) \tag{1}$$

where w_0 stands for the focused laser beam spot radius on the focal plane, F_{th} represents the ablation threshold fluence, and F_0 is the peak fluence which is given by:

$$F_0 = \frac{2E_0}{\pi w_0^2} \tag{2}$$

Where E0 represents the energy of a single peak pulse of the laser. After laser ablation on the workpiece surface, the function relationship between the ablation depth H and the peak laser flux F0 can be written as:

$$H = h^{-1} N \ln\left(\frac{F_0}{F_{th,N}}\right) \tag{3}$$

where h represents the ablated depth by a single-pulse laser.

3. Simulation

3.1 Laser-focused spot energy profile

A femtosecond laser is used to illuminate the surface of a copper workpiece. The femtosecond laser (Spiritone 1040-8-SHG, Newport Spectral Physics Technologies, Inc.) uses a central wavelength of 1040 nm and a pulse width of 400 fs. The monopole energy E_0 ranges from 1.09 μJ to 8.00 μJ. Fig. 2 depicts a mathematical model built to investigate the forming mechanism of single-pulse ablative surface profiles. As depicted in the figure, the relationship between the sectional profiles and the sectional profiles of the laser-ablated monocrystalline silicon workpiece based on the above parameters is illustrated.

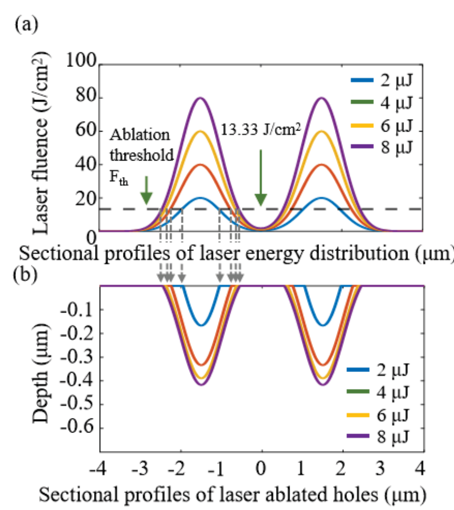

Fig.2. Mathematical model built to investigate the forming mechanism of a single-pulse ablative surface profiles. (a) Sectional profiles of laser energy distribution. (b) Sectional profiles of laser ablated workpiece.

3.2 Morphology of single-pulse ablated nanowires

Fig. 3 illustrates an ablation model of the nanowires in which 3D profiles of the ablated nanowires with various laser pulse energies on a

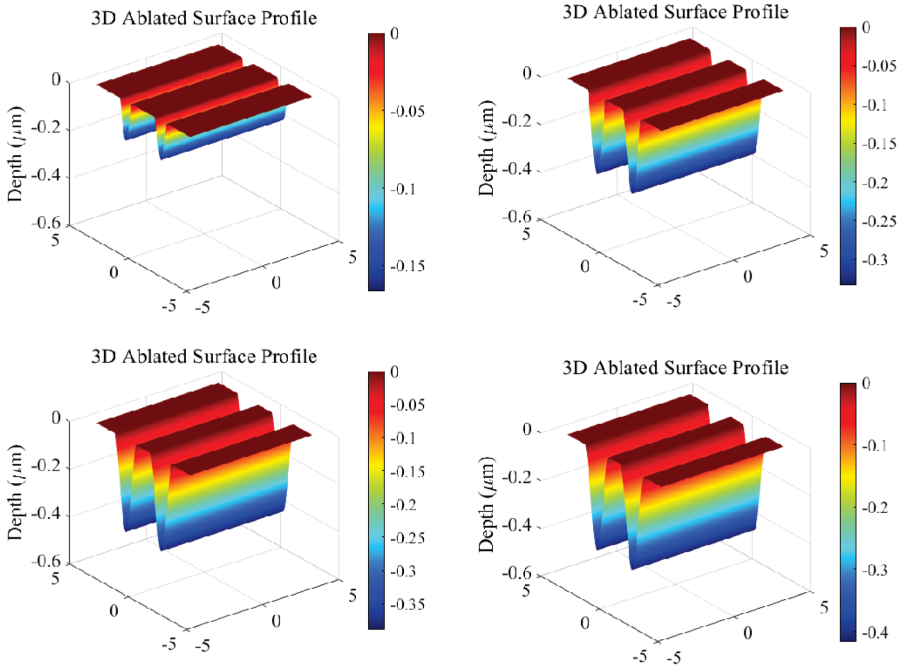

Fig.3. Simulation results of the ablation model of the nanowires under different pulse energy of (a) 2 μJ, (b) 4μJ, (c)6 μJ, (d)8 μJ, respectively.

monocrystalline silicon workpiece are illustrated. As can be seen in the figures, the depth of ablation depths on both sides increases as the single pulse ablation energy increases from 2 μJ to 8 μJ, which is in good agreement with the ablation mathematical model established in Figure 2. With the increase of the ablation energy, the laser ablated nanowires become more and more obvious, and the diameter of the nanowires becomes smaller, which provides basic guidance for selecting laser processing parameters for ultrafast laser processing of nanowires.

4. Conclusions

Nanowire has been widely used for its outstanding electrochemistry, optical, and mechanical properties, especially in its application as cathode materials in lithium-ion batteries. In this paper, a novel nanowire processing method by the use of an ultrafast laser with an optical 4f system for laser energy distribution modulation to directly process nanowires on the target material has been proposed, which can be directly fabricated on a target. A mathematical model is built to investigate the forming mechanism of single-pulse ablative surface profiles based on which the ablation model of nanowires has been established. Theoretical analysis and computer simulation have shown that the proposed method might be a simple and cost-effective approach for large-scale, low-cost preparation of nanowires.

ACKNOWLEDGEMENT

This research was supported by the National Key R&D Program of China (Grant No. 2022YFB3403603, 2022YFB3403602, 2020YFB2007600), the National Natural Science Foundation of China (Grant No.51975522), and the Zhejiang Provincial Natural Science Foundation of China (Grant No. LY19E050018). Chongqing Talent Project (Grant No. cstc 2022ycjh-bgzxm 0098), National Natural Science Foundation of China (Grant No. 52175495), National Natural Science Foundation of Chongqing (Grant No. CSTB2023NSCQ-LZX0088).

REFERENCES

1. Son, Y., Yeo, J., Moon, H., Lim, T. W., Hong, S., Nam, K. H., Yoo, S., Grigoropoulos, C. P., Yang, D. Y., & Ko, S. H. (2011). Nanoscale electronics: digital fabrication by direct femtosecond laser processing of metal nanoparticles. Advanced materials, 23(28), 3176–3181.
2. S. Hong, J. Yeo, G. Kim et al. (2013). Nonvacuum, Maskless Fabrication of a Flexible Metal Grid Transparent Conductor by Low-Temperature Selective Laser Sintering of Nanoparticle Ink. ACS Nano, 7(6), 5024-5031.
3. D. Lee, D. Paeng, H. K. Park et al. (2014). Vacuum-Free, Maskless Patterning of Ni Electrodes by Laser Reductive Sintering of NiO Nanoparticle Ink and Its Application to Transparent Conductors. ACS Nano, 8(10), 9807-9814.
4. I. Park, S. H. Ko, H. Pan et al. (2008). Nanoscale Patterning and Electronics on Flexible Substrate by Direct Nanoimprinting of Metallic Nanoparticles. Advanced Materials, 20(3), 489-496.

5. O. Vazquez-Mena , G. Villanueva , V. Savu , K. Sidler , Li, Y., & Hong, M. (2020). Parallel laser micro/nano-processing for functional device fabrication. Laser & photonics reviews, 14(3), 1900062.
6. You, K., Yan, G., Luo, X., Gilchrist, M. D., & Fang, F. (2020). Advances in laser assisted machining of hard and brittle materials. Journal of Manufacturing Processes, 58, 677-692.
7. Chen, J., Lu, X., Wen, Q., Jiang, F., Lu, J., Lei, D., & Pan, Y. (2021). Review on laser-induced etching processing technology for transparent hard and brittle materials. The International Journal of Advanced Manufacturing Technology, 117(9), 2545-2564.
8. Zhang, H., Hasegawa, S., Toyoda, H., & Hayasaki, Y. (2022). Three-dimensional holographic parallel focusing with feedback control for femtosecond laser processing. Optics and Lasers in Engineering, 151, 106884.
9. Hasegawa, S., & Hayasaki, Y. (2021). Femtosecond laser processing with adaptive optics based on convolutional neural network. Optics and Lasers in engineering, 141, 106563.
10. Liang, Y. Y., Tian, F., Luo, J. B., & Yang, G. G. (2006, October). Design of high precise focusing system in laser direct writer. In Journal of Physics: Conference Series (Vol. 48, No. 1, p. 192). IOP Publishing.
11. Hsu, W. Y., Lee, C. S., Chen, P. J., Chen, N. T., Chen, F. Z., Yu, Z. R., ... & Hwang, C. H. (2009). Development of the fast astigmatic auto-focus microscope system. Measurement Science and Technology, 20(4), 045902.
12. Chen, C., Shimizu, Y., Sato, R., Matsukuma, H., & Gao, W. (2020). An off-axis differential method for improvement of a femtosecond laser differential chromatic confocal probe. Applied Sciences, 10(20), 7235.
13. Zhao, R., Chen, C., **ong, X., Chen, Y., & Ju, B. (2023). An enhanced chromatic dispersion probe for simultaneous measurement of dual-axis absolute and relative displacement with nanometric resolutions. Measurement Science and Technology, 35(2), 025006.
14. Chen, C., Sato, R., Shimizu, Y., Nakamura, T., Matsukuma, H., & Gao, W. (2019). A method for expansion of Z-directional measurement range in a mode-locked femtosecond laser chromatic confocal probe. Applied Sciences, 9(3), 454.
15. Chen, C., Ng, C. K., Zhang, F., Xiong, X., Ju, B. F., Zhang, Y., ... & Chen, Y. L. (2022). Towards obtaining high-quality surfaces with nanometric finish by femtosecond laser ablation: A case study on coppers. Optics & Laser Technology, 155, 108382.
16. Ng, C. K., Chen, C., Yang, Y., Zhang, F., Ju, B. F., & Chen, Y. L. (2024). Femtosecond laser micro-machining of three-dimensional surface profiles on flat single crystal sapphire. Optics & Laser Technology, 170, 110205.
17. Chen, C., Zhang, F., Zhang, Y., Xiong, X., Ju, B. F., Cui, H., & Chen, Y. L. (2022). Single-pulse femtosecond laser ablation of monocrystalline silicon: A modeling and experimental study. Applied Surface Science, 576, 151722.
18. Goodman, J. W. (2005). Introduction to Fourier optics. Roberts and Company publishers.
19. Chen, X., Nakamura, T., Shimizu, Y., Chen, C., Chen, Y. L., Matsukuma, H., & Gao, W. (2018). A chromatic confocal probe with a mode-locked femtosecond laser source. Optics & Laser Technology, 103, 359-366.
20. Wilson, T., & Sheppard, C. (1987). Theory and practice of scanning optical microscopy. Journal of the Optical Society of America A, 4(3), 551-560.