Sensors and Actuators A 225 (2015) 111–118

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Modeling and analysis of the droplet-ultrasonic stage system for nano concentration

Pengfei Zhu, Junhui Hu*

State Key Lab of Mechanics and Control of Mechanical Structures, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China

ARTICLE INFO

Article history:
Received 5 September 2014
Received in revised form 6 February 2015
Accepted 10 February 2015
Available online 18 February 2015

Keywords:
Ultrasonic stage
Droplet
Acoustic streaming
Nano concentration

ABSTRACT

In this work, a droplet-ultrasonic stage, in which a micro droplet located at the center of the ultrasonic stage is used to concentrate nanoscale material, is modeled and analyzed by the finite element method. The computation method is verified by experimental results, and the acoustic streaming pattern inside the droplet is revealed, which can well explain the operating principle. Moreover, the effects of the vibration velocity, droplet size, ultrasonic stage topology and size, and droplet's sound attenuation coefficient on the acoustic streaming field are also investigated and clarified. The results show that the concentrating capability can be maximized without sacrificing the concentrating stability by properly increasing the droplet volume, and disposing a cylindrical groove in the center of the ultrasonic stage's substrate. Also, it is found that a thin substrate and thick piezoelectric ring are helpful to enhancing the concentrating capability without sacrificing the concentrating stability.

1. Introduction

Acoustic streaming is a kind of macroscopic flow caused by a sound field [1–4], collapse of a vibrating bubble [5] or solid vibration [6]. The conventional applications of acoustic streaming include cleaning [7], dispersion [7], mixing [8], non-contact driving [9], etc. Recently, acoustic streaming is applied to trap, position, orientate and rotate nanowires [6,10–12], and concentrate nano entities [13,14]. And this technology is termed ultrasonic nano manipulation [5].

Concentration of nanoscale entities has large applications in the graphene industry, sample extraction, high-sensitivity biosensing, crystal growth, artificial organ production, etc. Ultrasonic concentration of nanoscale entities utilizes acoustic streaming generated by an ultrasonic stage or vibrating needle to flush nanoscale entities to the central area or symmetric axis of an acoustic streaming field, and concentrate the nanoscale entities with a controllable shape. Experiments have shown that this technology can be used to form a round spot or linear line of nanoscale entities. The spot diameter can be controlled by the acoustic streaming field, and it is up to several hundred microns in the experiments [13]. The length and width of the linear line can also be controlled by the acoustic streaming field, and the length is several centimeters or even longer [14]. They have shown the capability of effectively concentrating nano samples in a solution. Moreover, just like other piezoelectric devices, devices used in the technology may have a simple and compact structure. However, studies on the acoustic streaming employed in this technology are still very scarce, which hinders its applications.

The authors proposed a method of forming a round spot of nanowires in a droplet [13]. In the method, nanowires in a droplet at the center of an ultrasonic stage may move to the stage center and form a round spot, and this spot of nanowires will still exist even after the droplet dries. Although this technique has promising application potential in graphene industry, biotechnology and material engineering, the effects of the device parameters and working conditions on the acoustic streaming inside the droplet are still known little. In this work, acoustic streaming in the droplet at the center of an ultrasonic stage is analyzed by the finite element method (FEM), and its operating mechanism and the effects of the device parameters and working conditions on the acoustic streaming are clarified. Some of the theoretical results are compared to the experimental ones, and they have good agreement, which verifies the FEM method. The results obtained in this work are useful in the customized design and application of the droplet-ultrasonic stage system.

2. Construction of the device

Fig. 1 shows the structure and size of the ultrasonic stage used for the concentration of nanoscale material. The ultrasonic stage

* Corresponding author. +86 25 8489 1681.
E-mail address: ejhhu@nuaa.edu.cn (J. Hu).

http://dx.doi.org/10.1016/j.sna.2015.02.014

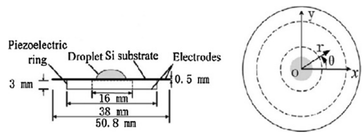

Fig. 1. The structure of the droplet-ultrasonic stage system used for nano concentration.

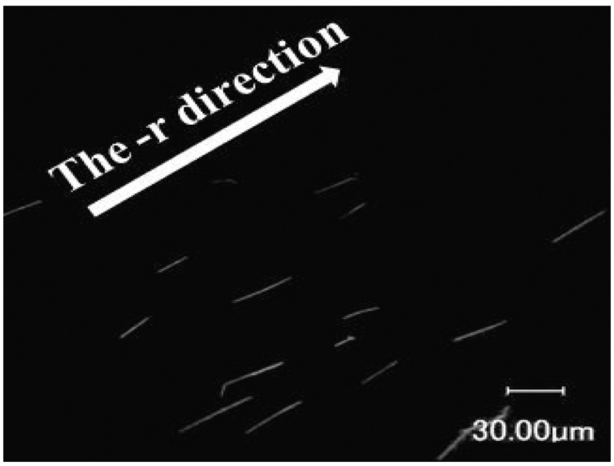

Fig. 2. Silver nanowires driven by acoustic streaming and moving towards the center of the ultrasonic stage.

consists of a circular silicon substrate and a piezoelectric ring bonded onto the silicon substrate by conductive adhesive. The silicon substrate has a diameter of 50.8 mm and a thickness of 0.5 mm, and its material parameters are listed in Table 1. The piezoelectric ring, concentric with the silicon substrate has an inner diameter of 16 mm, outer diameter of 38 mm, and thickness of 3 mm; it is polarized in the thickness direction. The material property parameters of the piezoelectric ring are shown in Table 2.

With a 60 Vp-p operating voltage applied to the piezoelectric ring, the ultrasonic stage resonates at 21.3 kHz. There is a vibration peak at the center of the ultrasonic stage, and the vibration mode of the ultrasonic stage is symmetric about the center. When the vibration velocity amplitude at the center point is proper, nano material such as AgNWs in the droplet and on the substrate surface may move to the center of the ultrasonic stage and form a round spot. Fig. 2 is an image showing the AgNWs driven by acoustic streaming and moving towards the center of the ultrasonic stage.

3. Analysis method

When the silicon substrate is excited to vibrate by the piezoelectric ring driven by a proper voltage, it excites an acoustic field in the

Table 1
Material parameters of the silicon substrate and adhesive material.

Parameter	Material	
	Silicon substrate	Adhesive (epoxy Stycast 2850FT)
Young modulus	130×10^9 [Pa]	10^9 [Pa]
Poisson's ratio	0.28	0.38
Loss factor	0.01	0.02

Table 2
Material parameters of the piezoelectric ring.

d_{31} [C/N]	-145×10^{-12}	Q_m	2000
d_{33} [C/N]	325×10^{-12}	$\tan\delta$	0.3%
ρ [kg/m^3]	7700	k_p	0.59

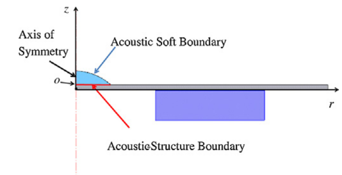

Fig. 3. A two-dimensional axisymmetric model and its acoustic boundary conditions.

droplet located at the center of the ultrasonic stage, which generates an acoustic streaming field inside the droplet. Meanwhile the vibration of the droplet applies a force on the ultrasonic stage. Thus an acousto-piezoelectric coupling physical model is considered for the numerical computation in this work. The COMSOL Multiphysics software, which is relatively strong in dealing with multiple physical field problems, is used to establish and solve the model. The numerical simulation can be split into four steps. First, vibration displacement of the ultrasonic stage with a droplet at its center is solved. Second, the vibration velocity and sound pressure in the droplet are calculated by solving the sound field in the droplet. Thirdly, driving forces of the acoustic streaming such as the spatial gradients of the Reynolds stress and the time average of the 2nd order sound pressure are calculated. Last, the acoustic steaming in the droplet is solved.

When the droplet is located at the center of the ultrasonic stage, the whole model is symmetric about the axis of the device. Thus, a two-dimensional axisymmetric model shown in Fig. 3 is used in the practical computation for saving computation time. In the computation, the acoustic field in the droplet and the vibration of the ultrasonic stage are coupled by the acoustic structure boundary between the droplet and substrate, which means the droplet and substrate have the same acceleration at their common boundary. Also, because ultrasonic wave attenuates quickly in air, the boundary between the air and droplet is set to be acoustically soft, that is, the acoustic pressure $p = 0$.

The vibration of the piezoelectric ring, substrate and adhesive layer is controlled by the following equations.

$$-\rho_s \omega^2 \mathbf{u} - \nabla \cdot s = \mathbf{F_V} e^{i\phi} \quad (1)$$

$$s = c_E : \varepsilon - \mathbf{e^T} \cdot \mathbf{E} \quad (2)$$

$$\varepsilon = \frac{1}{2}[(\nabla \mathbf{u})^T + (\nabla \mathbf{u})] \quad (3)$$

$$\mathbf{E} = -\nabla V \quad (4)$$

where ρ_s is the density of the elastic structure, $\omega = 2\pi f$ is the angular frequency, $\mathbf{u}$ is the displacement, and $\mathbf{F_V} e^{i\phi}$ is the alternative external load which is zero in the model, symbol: represents the double-dot tensor product (double contraction), c_E is the elastic matrix, $\mathbf{e^T}$ is the transpose of piezoelectric coefficient matrix, s is the stress tensor, ε is the strain tensor, $\mathbf{E}$ is the electric field, and V is the electric potential. The ∇ operating on a vector means the divergence of the vector, and ∇ operating on a scalar means the gradient of the scalar. $\mathbf{e^T}$ and $\mathbf{E}$ are zero for the substrate and adhesive layer.

The acoustic pressure is controlled by the following equations:

$$\nabla \cdot \frac{1}{\rho_c}(\nabla p) - \frac{k_{eq}^2 p}{\rho_c} = 0 \quad (5)$$

$$k_{eq}^2 = \left(\frac{\omega}{c_c}\right)^2 \quad (6)$$

$$c_c = \frac{\omega}{k}, \quad k = \frac{\omega}{c} - i\alpha, \quad \rho_c = \frac{\rho_f c^2}{c_c^2} \quad (7)$$

where p is the acoustic pressure, ω is the angular frequency, c is the sound speed, ρ_f is the density of fluid in the droplet, α is the