Sensors and Actuators A 147 (2008) 6–16

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

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

An efficient approach of handling and deposition of micro and nano entities using sensorized microfluidic end-effector system

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ARTICLE INFO

Article history:
Received 17 January 2007
Received in revised form 15 March 2008
Accepted 16 March 2008
Available online 29 March 2008

Keywords:
Sensors
Carbon nanotubes
End effector
PVDF
Microfluidic handling
Deposition
Droplet control
Micro electronics
nanoelectronics

ABSTRACT

This paper presents a novel approach of handling and deposition of micro and nano entities using a microfluidic end effector system with in situ polyvinylidene fluoride (PVDF) sensing. The microfluidic end effector system consists of a DC micro-diaphragm pump, one region of flexible latex tube, a polyvinylidene fluoride (PVDF) sensor for in situ measurement of micro drag force, and a micropipette. The micropipette of the novel microfluidic end effector system has an internal diameter (ID) smaller than 20 μm which is used for microfluidic handling and deposition of submicron entities such as carbon nanotubes and DNA. The DC micro-diaphragm pump is automatically controlled via a voltage driver interfaced with a computer in order to effectively and efficiently control suction force and pressure during microfluidic handling and droplet control in micro and nano manufacturing. The design, calibration, and experimental implementation of the novel microfluidic end effector are carried out in the paper. The experimental results show the success rate for depositing carbon nanotubes between micro electrodes can reach close to 80%. Ultimately, the technology will provide a critical and major step towards the development of automated process for manufacturing of micro and nanoelectronics as well as for microfluidic droplet control, and drug delivery.

1. Introduction

Manufacturing processes, which are capable of efficiently assembling micro and nano devices, have been studied and investigated by many researchers in the field. The assembling of micro and nano devices involves transporting and releasing of micro and nano parts to desired position (and orientation) and the suitable forces have to be applied to these micro and nano entities.

In macro entity handling and releasing, these problem are already solved by mechanical clamps using interaction forces or geometrically constraining grippers to hold and move the relatively heavy objects [1]. For small objects, sticking effect becomes more dominant. Compared to the adhesion and electrostatic forces, the weight and inertia of the entity are neglected because they scale with the cube of the size [2,3].

Researchers have published extensively on micro tools for microassembly and micromanipulation. For instance, in [4], Greitmann and Buser presented microparts handling using micro tweezer. In [5], Miyazaki proposed the utilization of adhesion effects to provide the gripping force. In microbiology, very sensitive living cells are handled in a liquid environment using glass pipettes as presented in [6]. In addition, a vacuum tool and different active releasing mechanisms are described in [7]. In [8,9], the use of a pneumatic end effector system for microsuction, microfluidic handling, and manipulation is described.

In designing submicron tools such as microgrippers, some major issues must be addressed. First, the operating targets are fragile and can easily be damaged, therefore, the force acting on the targets must be meticulously controlled. Unlike macro objects that are released by their self-gravitation, submicron entities need to be released by an active force, hence force regulation and releasing methodologies for submicron tools must be considered. In addition, if the force is too strong, the intended submicron object will be damaged or entirely destroyed. On the other hand, if the force is too weak, the submicron target will neither be picked up nor released. Second, the structure of the submicron tool must be simple and compact because of small or limited operation workspace, and the tool should be easily mounted or updated on the micro/nano robotic systems for the operations. Moreover, since submicron tools are very delicate, they have to be replaced frequently, resulting in operation efficiency reduction.

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0924-4247/$ – see front matter
doi:10.1016/j.sna.2008.03.021

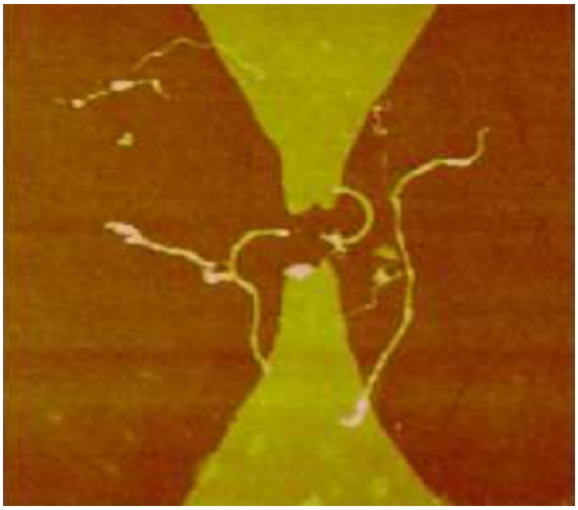

Fig. 1. AFM image illustrating carbon nanotubes between micro electrodes. The scanning range is 10 μm × 10 μm.

Microfluidic transport and control are the new trend and have become very important approaches in submicron handling, mixing, manipulation, and assembly. Moving fluid through a device or channel, regardless of the application, requires generating flow. The right amount of fluid must be precisely dropped at the desired location. Many methods have been proposed in recent years including micromechanical, electrowetting, thermocapillary pumping, surface-energy gradients, and electro-osmotic flow[10–13]. However, none of these methods are capable of performing a closed loop feedback control. To realize the maximum benefit of micro and nano fluidic droplet and handling, it becomes necessary to generate flow using tools that are integrated with sensor and have closed loop feedback control capability.

This paper addresses exploration and development of an effective and efficient solution for fluidic handling, droplet control, assembly, and manipulation on the submicron scale. Based on a pneumatic vacuum and pressure mechanism, a micro end effector, which is made from a micro pipette with ID smaller than 20 μm, is designed. The micro end effector (the micro pipette) is connected with the inlet/outlet of an effective micro diaphragm air pump through a tube. When voltage is applied to the air pump, micro suction or pressure force is generated at the tube end due to vacuum or pressure actions provided by the pump. The DC micro diaphragm pump is automatically controlled using a voltage driver interfaced with a computer. Also a high sensitive PVDF beam sensing buffer for micro force and flow rate measurement is built between the micro pipette and micropump. PVDF is a piezoelectric material that is transparent, mechanically durable, and flexible. It possesses two characteristics—sensing and actuation. When stress is applied to it, it becomes electrically polarized (electric charge) and the degree of polarization is proportional to the applied stress (direct effect/sensing). On the other hand, it deforms when electric field is applied to it (indirect effect/actuation). The new micro pipette-based end effector, micropump, and the PVDF sensing buffer are integrated into a closed loop system to provide precision controlled micro force and flow rate for fine microfluidic handling, droplet control, and manipulation.

One of the applications of the novel microfluidic end effector is to handle nano entities such as carbon nanotubes (CNTs) as illustrated in Fig. 1. In this paper, experiments focusing on efficiently handling and transporting carbon nanotubes in liquid acetone, and carbon nanotubes deposition between micro electrodes for manufacturing of sensors and electronics are demonstrated. The preliminary results have verified the effectiveness of the developed novel microfluidic end effector.

This paper is organized as follows. In Section 2, the fundamentals of fluid mechanics are reviewed. Section 3 describes the design of the novel microfluidic end effector. The sensing buffer and feedback loop approach of micro flow rate are presented in Section 4. In Sections 5 and 6, validation and calibration results of the related fluid mechanics are presented. Consequently, the experimental implementations and results on CNT handling and deposition are presented in Section 7. The work is concluded in Section 7.

2. Fluid mechanics for microfluidic end effector

2.1. Fundamental of surface tension and capillary force

Surface tension is a property of liquids arising from unbalanced molecular cohesive forces at or near the surface. The magnitude of the surface tension will depend upon the nature of both substances, liquid and liquid, or liquid and gas. In general, surface tension is a function of temperature and pressure. Surface tension of some common pairs of fluids at 25 ° C can be found in [14].

The force that results from surface tension is known as capillary force. Fig. 2 illustrates capillary rise due to surface tension in which the end of the capillary tube of radius *r*, is immersed in liquid [15]. For sufficiently small capillaries, a substantial rise of liquid to height *h*, is observed due to the force from surface tension. This force is known as the capillary force, F_{cap}. Equilibrium occurs when the force of gravity balances the capillary force. The balanced point can be used as a means to measure the surface tension.

As shown in Fig. 2, the surface of the capillary is not perfectly flat. Instead it curves up, sometimes down at the wall to form a meniscus as illustrated in the inset in Fig. 2. Taking into account that the material in this region also contributes to the force of gravity, the surface tension is approximately expressed as [15]

$$\gamma = \frac{1}{2}\rho g r \left(h + \frac{r}{3}\right) \tag{1}$$

where γ is the surface tension of the liquid, *r* is the radius of the capillary, *h* is the capillary rise, ρ is the density of the liquid, and *g* is the acceleration due to gravity. In Eq. (1), the angle between the

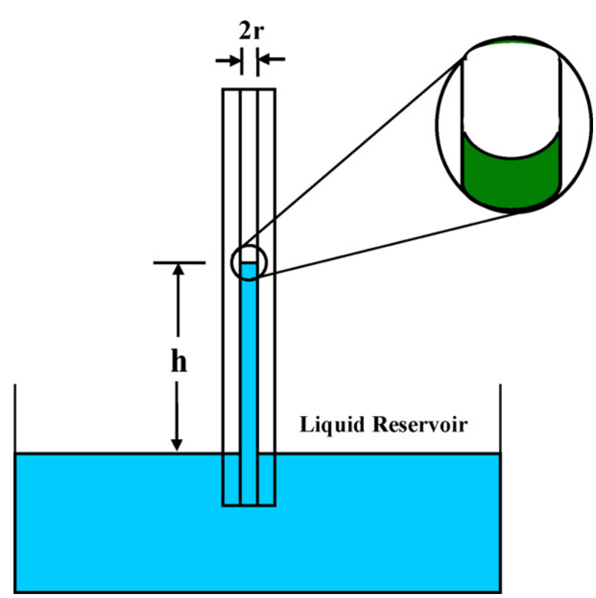

Fig. 2. Illustration of capillary rise due to surface tension.