MICRO/NANO DEVICES AND SYSTEMS INSPIRED FROM THE CONCEPT OF ICE CRYSTAL FORMATION

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Abstract

Developing sophisticated micro/nano device or system has been a big challenging task in many current state of the art science and technologies. As the tool to manipulate, fabricate, characterize, assembly and test the biological or non-living micro/nano objects, functional system in extremely small scale keeps receiving intense attentions over the industrial and academic area. This paper was aimed to systematically illustrate a new basic route to develop micro/nano devices and systems. The proposed approach was based on the formation of ice crystals, from which micro/nano aqueous objects or signals transmitting across them can easily be blocked, manipulated and analysed. In this way, a series of new conceptual micro/nano devices such as freeze tweezer, ice valve, freeze-thaw pump, electrical or optical signal switch and micro thermal analyzer etc. can be successfully developed. As examples, some latest advancement made in the author's lab was summarized and discussed. The working principles for some of these new systems were interpreted based on analysing the phase change behaviour of ice and its induced physical or chemical effects. Their innovative applications in a wide variety of micro/nano technology fields were suggested. Establishment of the present concept also raised many important fundamental issues for investigation. Clearly, through a combination between the freeze-thaw strategy and the mechanical, hydraulic, electrical, magnetic, acoustic, optical, and thermal effects etc., new inventions can still be very possible in the near future. Efforts made along this direction will create more and more useful tools for studying and implementing the micro/nano world.

1. Introduction

Many recent exciting sciences and technologies are significantly stimulated by the firmly set targets towards miniaturization. Building systems as compactly as possible has been a major theme either for engineering practices or academic investigations [1]. Countless endeavours were made over the last few decades to propose superior ways for fabricating, designing and characterization of new micro/nano device and system. Owing to the continuous advances in current science and technology, the sizes of the micro- or nano- machines are being dramatically reduced while maintaining their same or even higher performances. Among various disciplines to develop new technologies in the small category, those enabled from the thermal science plays a rather important role [2-4].

Up to now, many sophisticated micro/nano device or system has been invented. However, such enthusiastic endeavours often encounter bottleneck in many circumstances if still using the traditional approaches. Therefore, a variety of alternative strategies are being investigated [5]. This article was aimed to illustrate a new basic route for developing micro/nano devices and systems through the formation of ice crystals. As examples, some latest advancement made in the author's lab will be introduced. As outlined in Fig. 1, the fundamental concept for such innovations is enabled from the freeze-thaw operation. Via this approach, some brand new devices such as micro tweezers, micro valve, micro pump, micro switch (either for electrical or optical signals) and micro thermal analyser etc have been successfully invented. The working principles for several typical systems thus made will be explained. Particularly, their novel applications in a wide variety of micro/nano engineering fields will be highlighted and suggested. Future efforts worth of pursuing along this direction will be pointed out through out the paper.

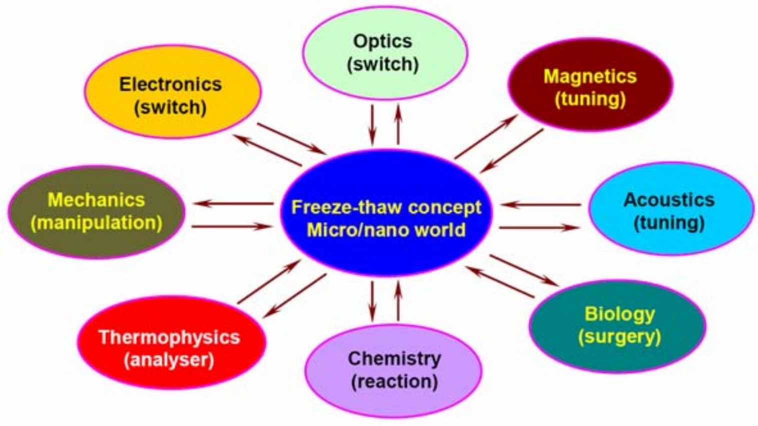


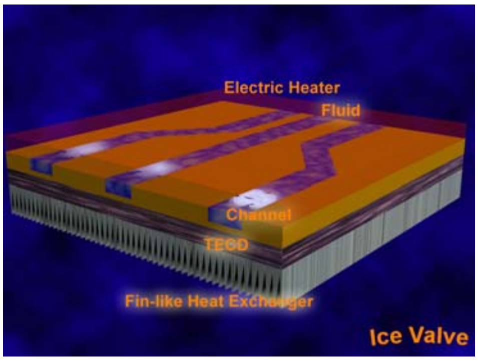
Fig. 1 New fundamental route for making micro/nano device and system by way of ice formation

2. Micro/Nano Scale Ice Valve

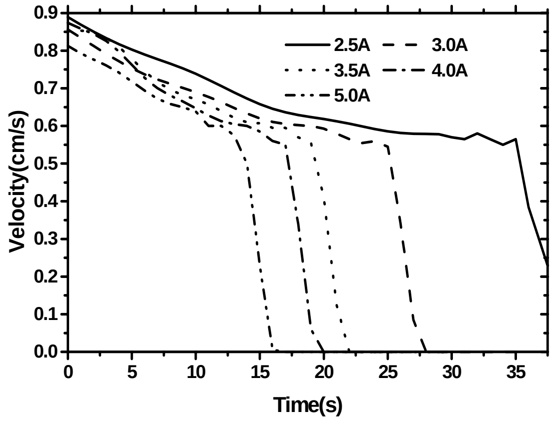
In a micro/nano fluidics pipeline system, valves are extremely important elements. During the past few decades, many micro-machined valves have been developed [6]. Most of them are consisted of a bulk micro-machined orifice and a deflectable sealing element, which generally can be a membrane, a ring mesa, a cantilever or a float. These valves execute their functions through actions between the orifice and the sealing element. Because of the existence of such moving elements, flow leakage around the valve is often unavoidable. To overcome such shortage, anti-leak measures have to be taken to enhance the sealing quality of the valves. However, adoption of the anti-leak unit also makes the valves too complex to implement, especially when facing the situations in a micro/nano flow channel. For a micro-machined valve, the inlet or outlet hole of the valve should be fairly large to allow for a high flow rate. If a rigid membrane material was used to block the hole, a relatively large size is needed and a strong force is necessary to deflect the membrane to the valve seat. Except for the leakage issue, the micro-size orifice and the small gap between the deflectable membrane cap and valve seat often generate an excessive flow resistance. This would lead to large pressure losses, especially when plenty of valves were integrated on a small chip. Still, many other additional aspects should be faced also make the fabrication of the micro/nano valves a tough issue, such as stiction, surface tension, cracking pressure, operational reverse pressure and so on.

Facing the above difficulties, we developed a purely electricity controllable ice valve [6] and its array system [7] as an idealistic unit to open or close the flow in a micro/nano channel, by freezing or thawing the liquid inside. Through this way, the leakage shortcoming was successfully resolved. Besides, the ice valve produces no resistance for the flow in the channel when operated. Especially, the smaller size for the channel, the more useful the ice valve will be. At the present stage, the ice valve may be regarded as one of the best control units for a nano-fluidic device. The most charming property of such valve lies in that no moving elements are necessary over the flow channel, and thus neither sealing elements nor valve seats are requested at all. As schematically shown in Fig. 2(a), this ice valve consists mainly of a thermoelectric cooling device (TECD), an array of working channels, a fin-like heat dissipater, and an optional electric heater. When a positive electric voltage is applied on TECD, the working fluid begins to freeze in a short time. With the formation of the ice crystals in the channels, the flow running across the valve will be automatically blocked with the decreasing of flow velocity (Fig. 2(b)). If switching the electric voltage to its opposite direction, the TECD begins to heat and thaw the “ice” in the valve, which consequently allows the liquid in the valve to resume to its flowing state again. In this sense, flow of the working fluid is obstructed just by itself but not any other external factors. Therefore, the ice valve puts an end to leakage basically.

Particularly, since no external elements were introduced into the flow channel, the ice valve appears as rather clean, which is pretty important for developing a fluidics based biochip analyser, where an extremely small pollution may cause the diagnostics failed.



(a)



(b)

Fig.2 Schematic of a TECD controlled ice valve array (a) and flow (velocity) responses during switching off operation of an ice valve channel (b)

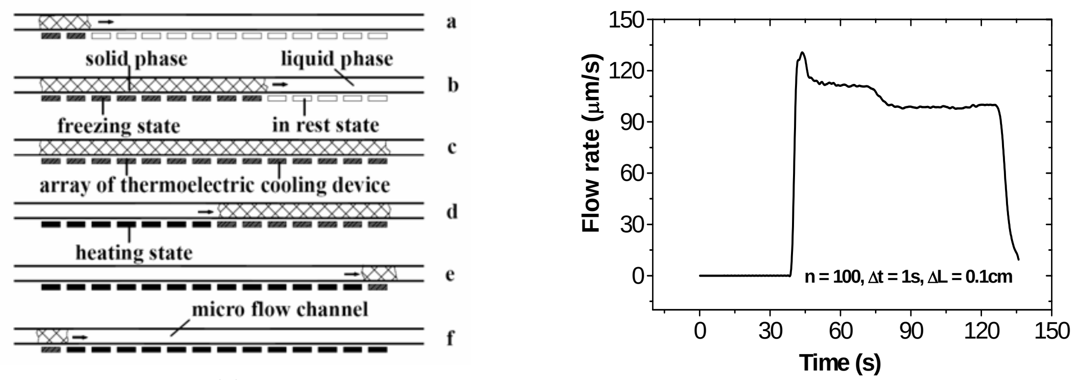
Except for the high sealing capability, the ice valve has another charming merit: easy to control. As one may feel, large-scale integration of micro-flow channel is becoming to show its prosperity recently [8]. A high-density micro-fluidic chip consists of thousands of micromechanical valves and hundreds of individually addressable reaction chambers. With self-supporting capability and being easily addressable, the electrically controllable ice valve is expected to find very promising applications in such system.

3. Micro/Nano Scale Ice Pump

Similar to the micro valve, micro pump is also a core element for a micro-fluidics system. Among many pumping mechanisms, thermal power has been proved rather flexibly useful. Through the cycling heating, the liquid inside a micro channel can be switched between its liquid and vapour phase [9]. As a result, they will serve to drive the fluid to flow. Such thermally enabled device can easily be miniaturized and integrated as a very powerful pump. However, the liquid-vapour based driving method may worsen the instability and uncertain driving due to strong expansion of liquid in the channel.

As an alternative, Gui and Liu [10] proposed a new conceptual ice peristaltic pump, which is to take use of the expansibility of the ice during its freeze/thaw phase change to drive the fluid in a micro channel. The principle of this freeze-thaw peristaltic pump can be illustrated by Fig. 3(a), which was consisted of a series of miniaturized thermal electric cooling devices (TECDs) aligned along the wall of the channel. If consequently switching on the TECDs to initiate cooling by following the order from left to right, the liquid in the channel will be made to condense part by part. As a result, due to ice density is lower than that of the water, it would expand and then push forward the liquid ahead of its solidified front which results in the flow of this part of liquid. When the liquid inside the channel was completely condensed, for example as shown in c-e stage (Fig. 3(a)), the TECD was switched to heating from left to the right direction, then the solidified ice inside the channel becomes thawed by following the same order. Since the liquid density is larger than its solid state, the thawing of the ice will induce an inhalation process. As a result, the liquid at the left hand side of the ice will be driven here. Keep this heating until all the frozen ice has been completely thawed. Then the liquid will be continuously driven to flow through the channel.

Repeating the above freeze-thawing process, the liquid flow will be successfully enabled. The flow rate realized by this freeze-thaw peristaltic pump has been predicted in the Fig. 3(b), where a relatively constant flow rate around 100 μm/s was generated.



(a) (b)

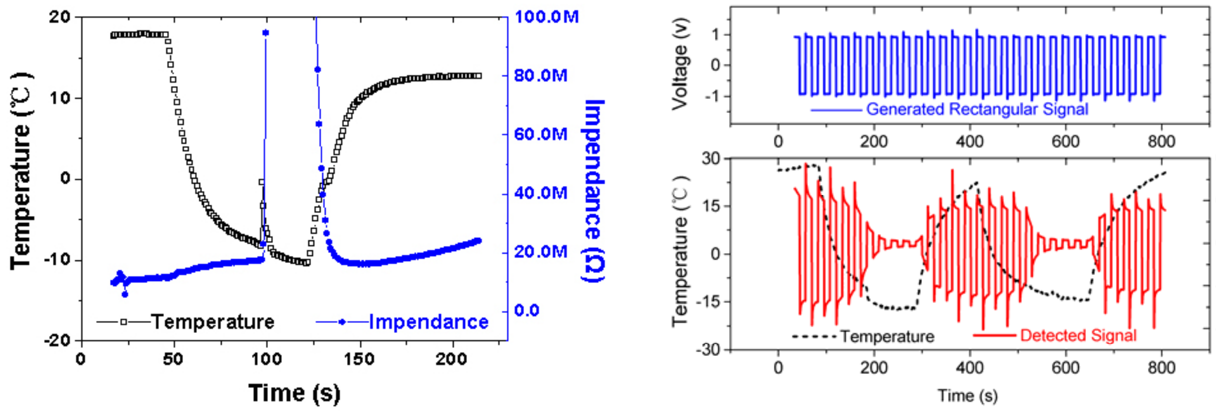
Fig. 3 Working principle (respectively reflecting 6 stages from a to f: freezing and heating of fluid) of freeze-thaw peristaltic pump (a); Theoretically predicted flow rate induced by 100 elements of a TECD array (b).

Compared with the vapour driven pump, the freeze-thaw pump could realize a much slow and stable flow pressure. Particularly, the cooling process will only cause a much weaker injury to the sample transmitted inside the channel, due to avoidance of high temperature. In addition, the energy consumption rate for such system could possibly be much smaller. More attractive merit still lies in that, no moving elements are needed and no leakage exists in this novel pump. If combined with the ice valve, a micro/nano fluidics system totally made of non-moving element can be built up for the first time. This will find interesting applications in future microfluidics system.

4. Micro/Nano Electrical Switch For Liquid Circuit

Liquid circuit, the construction of fluidic devices similar to electronic circuits, had ever been an active research field over the 1960s and early 1970s [11]. Recently, with the advent of miniaturized micro/nano fluidic technologies, there is an increasing demand for logical control of such devices. Some newly emerging fluidic devices such as oscillators, flip-flops, amplifiers, and logic gates were built and integrated into sophisticated control systems [11, 12]. In fact, nature has produced a great many different liquid circuits in a biological system. For example, the neural system serves as just one of such typical circuits, wired together to make up a complex network through which information spreads and processes. Following diverse and complicated biochemical reactions, neuron is able to receive process and transmit the signals over the synapses. The electrical impulses can pass through the body of the neurons by means of changes in the membrane potential [12]. Up to now, some new techniques have been developed to operate the growth of myocytes and neurons to assemble a functional network [13]. The neurons also have been inoculated onto the silicon chip to form a part of the neuron-semiconductor hybrid circuit [14], which will help to study the function of neurons and provide an opportunity to reveal the physical mechanisms of thinking. Clearly, if a micro- or nano-scale electrical switch can be fabricated to flexibly turn on/off the neuron, it should be an important aid for such endeavours.

However, operating living system is not as easy as controlling a solid electrical circuit. With the complexity and nonlinearity that can be introduced into the system through the use of multiphase flows or chemically responsive materials, few controlling or actuating elements have been demonstrated for flexibly operating the liquid circuit especially the biological network. Usually the commonly adopted switch is through a physical cutting to stop the current of electrical charges. But within a micro or even nano fluidic system, it is rather difficult to completely cut such current in the flow path just by a single mechanical valve. The troubles mainly come from the following factors. Firstly, traditional micro-machined valves are complex and have many components, which will make the control systems fragile and thus unreliable, saying nothing of their high cost. Secondly, because of the existence of moving elements in such valves, the electrical current could not be completely blocked due to the flow leakage around the valve. Lastly, if the valves are made of electrically conductive material, the electrical current is not controllable. To tackle such tough issue, the ice valve as developed before [6] can basically resolve most of the foregoing troubles. It turns out among the best candidates for the electrical control of liquid circuit. As had been revealed, electrical impedance of biological materials could become almost infinitely large as an insulation material during the processes of freezing [15]. Therefore freezing the target circuits will significantly increase the electrical resistance (Fig. 4(a)) and thus prevent the electrical signal from transmission across them (Fig. 4(b)). It is started from this basic concept, we had established a flexible tool of ice electric switch for studying the biological circuit network or the like [16]. Capability of the new approach by using freezing to stop the electrical signal transmission along a liquid circuit or some biological system receives excellent experimental support.



(a) (b)

Fig. 4 (a) Transient temperature and impedance of the neurons of a crucian nerve during its freezing and thawing process; (b) Transient temperature and voltage signal detected from the earthworm during a freezing process. The upper rectangular wave signal came from the signal generator.

As is well known, signal transmission and processing over the wet circuit of a liquid-like biological network system has been a great important topic in revealing the life phenomena or designing some semi-biology and semi-machine micro-system. We proposed for the first time to implementing the turning off properties of the liquid circuit in a biological network or a generalized conductive micro-fluidic system through introducing ice switch [16]. By selectively freezing part of the electric aqueous solution inside the circuit, the ions to conduct the electric current along a specific direction was completely shut off due to formation of the frozen insulation solution (Fig. 4(a), (b)). After thawing, the electrical current along the micro-fluidic circuit will resume to its turning-on status again. For demonstrating this concept, some experiments were performed to test the transient electrical impedances of the solution or biological system subject to freezing and heating and convincing results were obtained as indicated by Fig. 4(b) [16]. Clearly, with the working of the TECD, the amplitude of the detected signal wave gradually decreases until finally drops to be close to zero. The reasons for this phenomenon can be attributed to that the impedance of the solution increased sharply during freezing and electrical signal intensity therefore fell down. Here, a quadrate wave was applied on the liquid circuit. The signal transmission across it during the freezing was ultimately cut off. The working performances of the freezing electric switch depending on controlling the conductive liquid circuit were tested and its potential applications in electrophoretic analysis, liquid chromatogram analysis or especially controlling the signal transmission across the neural network (for example the pain prevention) are worth of investigation in the near future. This electrical switch based on ice formation opens a new way for studying and implementing the wet electrical circuit.

5. Freeze-Thaw Micro/Nano Network Optical Switch

Recently, optical network has been in the stage of entering daily life. With the rapid advancement of optical communication technology, improving the performances of optical switch, a core element in optical network, becomes extremely important. Among many novel optical switches ever developed, those enabled from the thermal or fluidics effect are pretty attractive [17], due to that they were rather easy for large scale integration, which is very beneficial for constructing an optical network. Some typical inventions in this area can be listed as but are not limited to the followings such as the thermal optical effect switch, the thermally enabled mechanical optical switch, the vapour bubble optical switch based on evaporative phase change process, the thermo-capillary optical switch and more other types of micro-fluidics optical switch. It was now proved that micro/nano scale thermal and fluidic methods have unique virtues in flexibly controlling the signals transmitting across the optical network. Clearly, any innovation along this approach would lead to invention of new optical switch. However, at the present time only very limited efforts were made to address such issues. In fact, there are many opportunities for the basic or practical research in developing a thermally enabled optical switch.

Noticing that solidification of a specific liquid medium would lead to its variation in optical properties (such as refractive index) and light will then be reflected at the solid-liquid interface and transmitted to another direction, we proposed a new conceptual optical switch using phase change of refractive index matching liquid to manipulate the transmission of the optical signals. Depicted in Fig. 5(a) is a schematic structure for such optical network consisted of 3×3 freeze-thaw switches [18]. Here, the optical switch drawn as deep blue colour represents that the liquid inside the gap of switch has been completely frozen, while the switch in shallow blue colour is for that the liquid remains at its original state. Using this device, the optical signals coming from six ports can be flexibly regulated. For example, the signal from the I_{10} port could be completely reflected at the interfaces of optical switches A and B (where the liquid was in frozen status) and then transmitted out through the port of I_{11}. Similarly, the optical signal from the port I_{20} would be completely reflected by the switch unit of C and then runs out through the port I_{21}. The signal from port I_{30} will not be manipulated by any switch unit but just transmits along its original direction, i.e. consequently runs across three switches until finally comes out from port I_{31}. This is because the working medium in these three optical switches are all in liquid status (drawn as shallow blue colour), therefore the signal will not be affected. The optical signal from I_{40} can be completely reflected at the interface of freezing switch A and then runs out from port I_{41}. From the picture, one can find that the optical switch A has been particularly adopted to flexibly control the optical signals coming from two directions. It should be pointed out that, what has been presented in the Fig. 5(a) is only a typical structure. More configurations and combination for the optical network can still be possible through certain specific designing in the near future.

There are many different choices for the working liquid used in the freeze-thaw optical switch. Of particular consideration lies in that, its condensation point should not be too low. Otherwise, a large energy consumption rate will be needed to freeze the liquid. In addition, a long period for the optical switch to react will be un-avoidable. Such points should be carefully considered when developing a practical freeze-thaw optical switch. In our previous studies, several liquids have been tested such as dimethylsulfoxide (DMSO), whose condensation point is around 18℃ and refractive index at $1.47 \sim 1.48$, and chemicals $C_{10}H_{12}O$ with condensation point at 11~13℃ and refractive index at 1.5185-1.5205. Comparative experiments show that $C_{10}H_{12}O$ appears as a kind of good refractive index matching liquid which could possibly be used in future optical switch, if its toxicity can be lowered or completely prevented. The feasibility of the freeze-thaw optical switch has been verified in our previous studies from both theoretical analysis and preliminary experiments [18]. It was shown that this freeze-thaw optical switch could be used to flexibly regulate the transmission or reflection of the coming light inside the wave guide and thus can be developed as a very useful device in the field of optical communication.

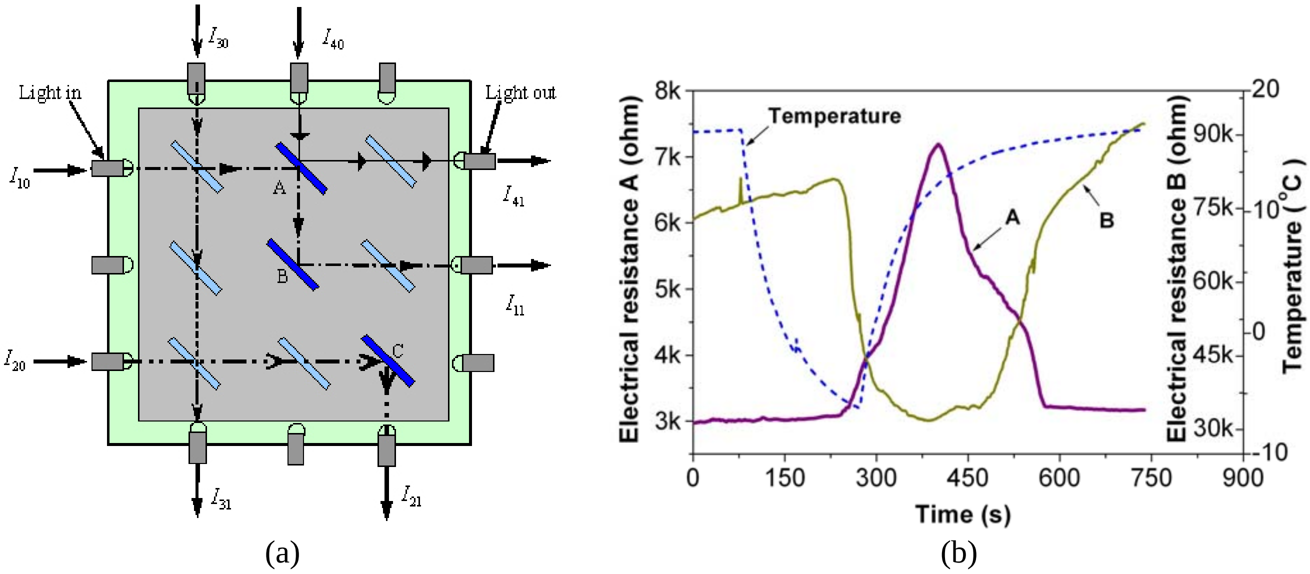


Fig. 5(a) Optical network controlled by a 3×3 freeze-thaw optical switch array; (b) Temperature response of liquid and transient electrical resistances of two optical sensors A and B during freezing and thawing process of the liquid.

So far, we have obtained some typical experimental curves as depicted in Fig. 5(b), which indicated the switching on and off property of the laser optical signals transmitting across the freeze-thaw optical switch [18]. In such test, a small amount of liquid $C_{10}H_{12}O$ was filled into the thin gap of two parallel optical lenses to form the basic unit of an optical switch. A thermal couple was embedded in advance into the liquid to monitor its temperature response. Meanwhile, two optical sensors A and B were perpendicularly positioned in the two transmission paths of the optical signals to monitor their intensity. A large electrical resistance represents that no optical signal comes to the sensor while a small electrical resistance indicated that the optical signals has transmitted to this sensor. From the measurement as given in the Fig. 5(b), it can be found that when the liquid $C_{10}H_{12}O$ was subject to freezing by a TECD, its temperature turns to gradually decrease until phase change occurs (indicated by the small jump in the temperature curve). At the same time, there appear two opposite responses in electrical resistances for the two optical sensors A and B during freezing and thawing process of the liquid confined in the gap of an optical lens. For example, when freeze phase change occurs, the resistance for the sensor A increases while that for sensor B decreases, representing that an optical signal had transmitted to the sensor B. Similarly, if stopping the freezing of the TECD, the liquid temperature will go up. And the resistance for the sensor A decreases while the measurement of sensor B increases, representing that an optical signal had transmitted to the sensor A. Clearly, it is in the phase change process of the liquid $C_{10}H_{12}O$, that the transmission direction of the optical signal was successfully shifted by the freeze-thaw optical switch.

The above device developed at the present stage is overall a proof-of-concept prototype. Much improvement can still be possible. Compared with the previously established vapour bubble optical switch which is enabled through heating liquid into vapour, the freeze-thaw optical switch has evident merits in realizing a rapid response and reducing energy consumption rate. If appropriately choosing the working fluid, a much smaller energy consumption and rapid response can be expected in the near future. This would be a valuable advantage over traditional bubble based optical switch.

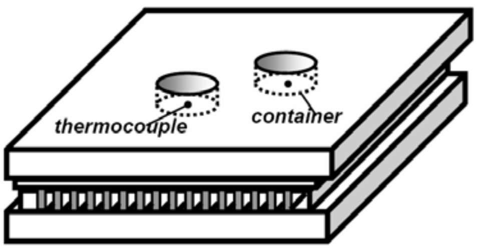
6. Micro/Nano Thermal Analysis System

In addition to controlling liquid or signals, the ice formation mechanism was also recently found significant in developing a basic tool to characterize the material properties [19]. Such innovation was stimulated from the urgent need of the cryomedical engineering practices. As is well known, freezing was used either to preserve or to kill the biomaterials. Thawing is the inverse process of a cryosurgery or cryo-preservation practice. At those widely different cooling and warming rates maximal preservation or destruction of biological materials is achievable. In order to obtain an optimal output, specific cooling and warming rates must be imposed during the cryo-medical process. Assessing the freezing and warming damage of the biological materials and correlating the final result to a specific program are thus of critical value for the practices.

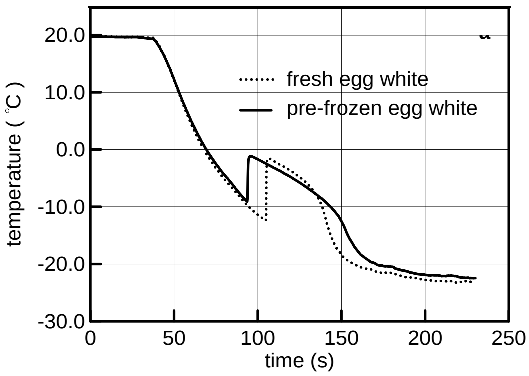
However, due to diversity in structure, composition, concentration and storage conditions for different biomaterials, no universal methods are currently available to assess their viability after cryo-preservation or surgery. The most typical evaluation ways generally include [19]: morphological and physiological observation, cell culture followed with biochemical testing, fluorescence detection, long-term histological evaluation, cell accounting by flow cytometric analysis, liquid chromatography, composition analysis, isotope marker method, electron spin resonance spectroscopy, nuclear magnetic resonance technique, oxygen or glucose consumption analysis, dye exclusion and dopamine release, dielectric measurement, differential scanning calorimetry, effective thermal conductivity measurement, and minimum cell-to-volume ratio, etc. Most of these efforts appear either too complicated or request tedious preparation, easily affected by the external factors, usually time consuming and expensive. Therefore, establishing a quick and cheap method to select the most appropriate freezing or warming program has long been an intriguing object. As has been realized, freezing or thawing affects biological systems at both nanoscale (molecular) and microscale (cellular) levels [20], which may induce changes in the structure and the composition etc. of a cell. And the site most easily damaged is the cell membrane that surrounds the intracellular solution. With typical thickness at 10nm, the primarily impermeable membrane incorporates ion channels and other proteins that facilitate mass transfer between the intracellular and the extracellular solutions. The phospholipid bilayers that form the cell membrane undergo an abrupt phase change from a disordered fluid to solid when subject to an external freezing. This phase change temperature is strongly dependent on the composition of the phospholipids, their chain length and degree of saturation [20]. And the destructive freezing or warming will affect membrane's ability to separate effectively between the interior of the cell and the extracellular solution and to control the mass transfer, including the weak bond interactions that determine protein structure, cytoskeleton structures, and enzymeligand interactions. The other modes of freezing damage include denaturation of proteins in the dehydrated cells due to hypertonic concentrations and mechanical damage to cells due to formation of the intracellular ice [20]. Therefore, the mechanisms of the freezing injury can all be attributed to their effects to the cells especially the membranes. Correspondingly, warming has similar effects to damage a cell.

As is well known, when a small amount of liquid (except for glass-like materials) is cooled to below its equilibrium temperature, it does not immediately freeze but remains at a metastable supercooled state [19]. Shortly, a sharp temperature jump will happen in the liquid droplet, which is due to heat release during crystallization of water. This feature implied significant applications in material analysis, which in fact consists one of the most basic foundations for the differential scanning calorimeter. Without any doubt, material property is closely related to its freezing behaviour. Based on this principle, we established a method named as Freezing Curve Based Monitoring (FCBM) [19] to quickly evaluate the viability of biomaterials subject to freezing or thermal injury, which is hard to perform otherwise.

An integrated micro analysis device as ever fabricated was shown in Fig. 6(a), which is simple in structure and cheap to make. Preliminary freezing results demonstrated that minor changes in a biological material due to freezing or warming injury might result in a significant deviation in its freezing curve compared with that of the intact biomaterials (Fig. 6(b)). Several potential thermal indexes to quantify the material features can thus be set up [19]. Additional experiments were performed on several freezing and thawing processes of small amount of water on a cooling surface to test the effects of the droplet sizes, the measurement sites, the cooling strength and the cooling geometry etc. to the freezing responses of a water droplet. Their implementations in developing new micro analysis system were suggested [19]. Such method was also recently extended to develop a biological chip to batch select an optimum cryo-preservation protocol [21]. It is very possible this freezing curve based monitoring method may open a new strategy for the rapid evaluation of biomaterials subject to destruction in diverse fields.



(a)



(b)

Fig. 6 (a) Schematic for the viability evaluation device to apply cooling and record temperatures of biological signals. (b) Time dependent freezing curves for the liquid nitrogen pre-frozen and air slowly thawed egg white and the fresh egg white. Both samples are obtained from the same chicken egg and subject to the same cooling by TECD.

7. Micro/Nano Freeze Tweezer

Among many micro/nano technology areas, manipulating very small objects has been a big challenging task. Especially, such an endeavour in aqueous or wet environment has been a crucial target for bioengineering where manipulation of in situ biological object, such as DNA, protein or cell membrane, and tissues etc., is of particular importance [22-24]. Up to date, quite a few interesting ideas have been proposed, each of which has its specific capability. Some mechanisms based on thermal, mechanical, hydrodynamic or ultrasonic actuation were also developed. The biggest difficulty in a micromanipulation lies in its sophistication, precision and efficiency in handling and interaction with the objects. Previous methods usually manipulate object by pushing and touching. For example, AFM tip was proposed as the pushing manipulator using the electrostatic force. However, using one AFM cantilever is limited to the simple mechanical manipulations such as pushing and cutting. More complex manipulation tasks such as pick and place are unsolved challenging problems at the nano scale. Usually, some micro/nano objects such as biological cell are so small and flexible that it is difficult to handle them by the manipulator. Non-contact method through laser trap, i.e. optical tweezer to manipulate object was also well established, which however may cause thermal damage to the object especially biological specimen, due to possibly over heating by the laser beam.

Through introducing a brand new concept, we proposed to use a small volume of nucleotide ice generated at the tweezer tip to manipulate micro or nano objects in aqueous states (Fig. 7) [25]. The device thus made was named as freeze tweezer. It is the ice ball formed around the tweezer tip that serves as the gripe. Picking and placing an object by using the new tweezer was demonstrated as an excellent alternative over some traditional approaches. Therefore as reported by the scientific media, invention of the freeze tweezer indicates that "micro tweezers have ice gripe" (http://www.trnmag.com/Stories/2004/012804/Micro_tweezers_have_ice_grip_Brief_012804.html). In this method, positioning resolution can be controlled through regulating the freezing strength of the ice. With the formation of an ice ball at the tweezer tip, part of the object surface can be embraced into it. Then an adhesion force will be generated between the object and the ice ball, which is strong enough to manipulate the object (Fig. 8). Measurement on the force due to ice formation can be performed through a delicate weighing method by gently adding balancing weight one by one. Such force was found sometimes to be several times larger than the weight of the object. If one wishes to release the object, stopping freezing (tweezer can naturally re-warm itself in the air) or just heating the tip and thawing the ice ball there will solve the problem. Precise control of the object can be performed through combining the freeze tweezer with some accurate controllers such as a piezoelectricity (PZT) stage. If an ice ball in micro or nano scale was produced at the tip, the freeze tweezer could possibly realize a positioning resolution in micro or nano meter in the near future. Freeze tweezer has twofold functions: fix and move the object simultaneously and then do more complex manipulations such as rotate, stretch and twist. Usually, the surface of the object and tweezer tip serve as the nucleation site for the crystallization of ice. Therefore the most easily frozen area at the object surface is that nearest to the freezing needle. The tip is generally fabricated as in sharp and the smallest tip diameter ever achieved in our lab is 20㎛. Therefore if well controlled, only the object close to the tip will be contacted and grasped.

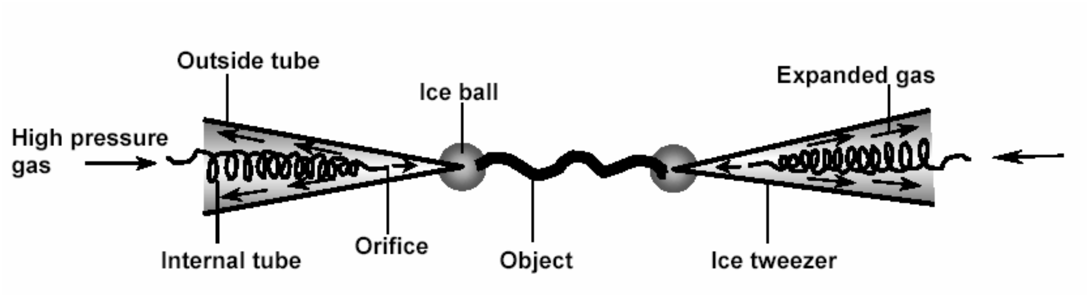
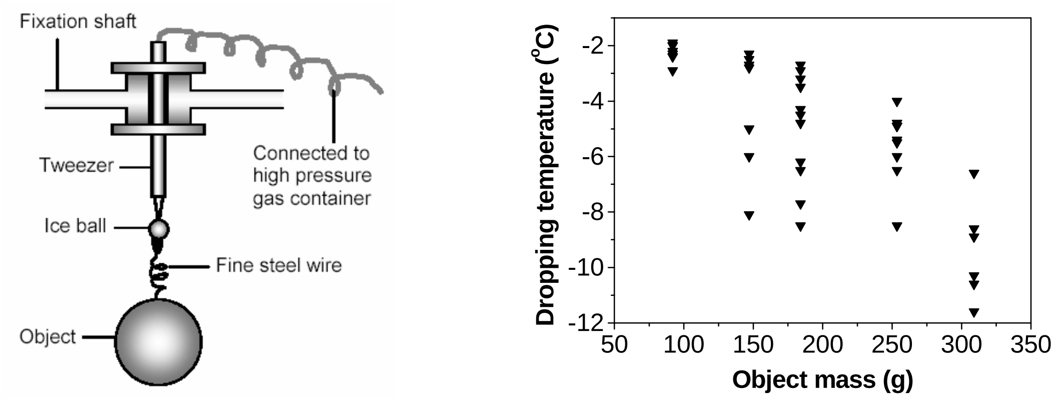


Fig. 7 Schematic application of two Joule-Thompson effect based freeze tweezers to stretch an object like a DNA string or a cell



(a) (b)

Fig. 8 Measurement of the object weight and the tweezer tip temperature (dropping temperature): (a) Experimental set up; (b) Relation between tweezer grasping force and tip freezing temperature.

The freeze tweezer works through freezing force of a small volume of nucleotide ice to manipulate mini/micro objects in aqueous state. Several prototypes of such device based on Joule-Thompson throttling effect have been fabricated and demonstrated in our lab for their applicability in manipulating a wide variety of objects (Fig. 7) [25]. Through regulating the freezing conditions of the cooler, an ice ball can be formed between the tweezer tip and the object it contacted and then pick the object up. This freezing force is capable of manipulating objects with any shape, electric charge, light or heavy, biological or non-living, on condition that the contacted area can be frozen. Successful manipulation of a series of specific objects presented in our previous study indicates that [25], it would be much easier for the freeze tweezer to handle objects with smaller size. Therefore further nano scale freeze tweezer following the same idea as above can be put forward which is expected to have exciting applications in micro/nano engineering field. Clearly, the new technique also raised quite a few new interesting fundamental issues related to the fabrication and practices of the freeze tweezer.

8. Conclusions

From the above description, it can be seen that all the micro/nano devices as described in the present paper are enabled from the formation of the ice crystals. This concept successfully initiated many novel technologies whose potential applications can be found in various disciplines. By way of the intentionally induced phase change of the liquid medium embedded inside the device, many external signals or objects can be flexibly manipulated or characterized. The present comprehensive discussion proposed a basic route to construct micro/nano system, which may have plausible merits over traditional approach in some special circumstances. Meanwhile, it also raised many new scientific issues worth of pursuing. For example, the fundamental insight into the freeze-thaw based device and transport phenomena reserved to be un-completely addressed. Particularly, heat transfer behaviours such as conduction, convective flow, freeze and thawing phase change etc. and their related physical or biochemical effects (such as electrical, magnetic, acoustic, optical and thermal effects of the ice and water, to name a few) in the micro/nano scale are expected to be different from those occurred in large scale [4]. Further, miniaturizations of most of the prototype devices are urgently needed, which may possibly open many new technologies in future micro or nano engineering fields. Our previous attentions are mainly focused on proof-of-concept. Tremendous efforts are still needed on the device design, fabrication, and performance test. Illustrations made in the present paper warrant further research along this direction in the near future.

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References

[1] M. J. Madou, Fundamentals of Microfabrication, CRC Press, 2002.
[2] C. L. Tien, A. Majumdar, and F. M. Gerner, Eds., Microscale Energy Transport, Taylor & Francis, 1998.
[3] M. Gad-El-Hak, Ed., The MEMS Handbook, CRC Press, 2001.
[4] J. Liu, Micro/Nano Scale Heat Transfer (in Chinese), Beijing: Science Press, 2001.
[5] G. K. Ananthasuresh, Ed., Optimal Synthesis Methods for MEMS, Kluwer Academic Publishers, 2003.
[6] L. Gui, and J. Liu, Ice valve for mini/micro flow channel, Journal of Micromechanics and Microengineering, vol.14, pp.242–246, 2004.
[7] L. Gui, and J. Liu, Study on micro-fluidic ice valve array system, pp.242-246, The 6th International Symposium on Heat Transfer, Beijing, China, June 15-19, 2004.

[8] T. Thorsen, S. J. Maerkl, and S.R. Quake, Microfluidic large scale integration, Science, vol. 298, pp. 580-584, 2002.
[9] Z. X. Li, M. R. Wang, X. B. Yao, and Z. Y. Guo, Pumping mechanism of thermally driven phase transition micropump, Microscale Thermophysical Engineering, vol. 8, pp. 31-41, 2004
[10] L. Gui, and J. Liu, Feasibility study on a freeze-thaw phase change peristaltic pump (in Chinese), Annual Heat and Mass Transfer Conference of the Chinese Society of Engineering Thermophysics, No. 043028, Jilin, China, 2004.
[11] P. Groisman, M. Enzelberger, and S. R. Quake, Microfluidic logic and control devices, Science, vol. 300, pp. 955-958, 2003.
[12] P. Greengard, The neurobiology of slow synaptic transmission, Science, vol. 294, pp. 1024-1030, 2001.
[13] K. Kojima, H. Moriguchi, A. Hattori, T. Kaneko, K. Yasuda, Two-dimensional network formation of cardiac myocytes in agar microculture chip with 1480-nm infrared laser photo-thermal etching, Lab on a Chip, vol. 3, pp. 292-296, 2003.
[14] M. J. Schulz, G. R. Kirikera, S. Data, and M. J. Sundaresan, Piesoceramic and nanotube materials for health monitoring, SPIE NDE, vol. 4702-03, pp. 17-28, 2002.
[15] T. H. Yu, Y. X. Zhou, and J. Liu, Low-frequency electrical impedance of biological materials subject to freezing and its implementation in cryosurgical monitoring, International J. Thermophysics, vol. 24, pp. 513-531, 2003.
[16] X. D. Bai, and J. Liu, Control of electrical signal transmission across the liquid circuits of biological network through freeze switch, Micronanoelectronic Technology, in press, 2006.
[17] X. P. Qu, and J. Liu, Research and application of micro thermal control techniques in optical network switches (in Chinese), Laser & Infrared, vol. 34, pp. 403-407, 2004.
[18] X.-P. Qu, and J. Liu, Freeze-thaw optical network switch (in Chinese), Laser & Infrared, in press, 2006.
[19] J. Liu, and Y. X. Zhou, Freezing curve based monitoring to quickly evaluate the viability of biological materials subject to freezing or thermal injury, Analytical and Bioanalytical Chemistry, vol.377, pp.173–181, 2003.
[20] B. Rubinsky, Microscale heat transfer in biological systems at low temperatures, Experimental Heat Transfer, vol. 10, pp. 1-29, 1997.
[21] L. N. Yu, J. Liu, Y. X. Zhou and Z. Z. Hua, Biological chip technology for quickly batch selecting optimum cryopreservation procedure (in Chinese), Issue 1, pp.21-26, 2006.
[22] P. Kim, C. M. Lieber, Nanotube nanotweezers, Science, vol. 286, pp. 2148-2150, 2000.
[23] C. A. Mirkin, Tweezers for the nanotool kit, Science, vol. 286, pp. 2095-2096, 2000.
[24] E. W. H. Jager, O. Inganas, I. Lundstrom, Microrobots for micrometer-size objects in aqueous media: potential tools for single-cell manipulation, Science, vol. 288, pp. 2335-2338, 2000.
[25] J. Liu, Y. X. Zhou, and T. H. Yu, Freeze tweezer to manipulate mini/micro objects, Journal of Micromechanics and Microengineering, vol.14, pp.269–276, 2004.