# ON EMERGING MICRO- AND NANOSCALE THERMOFLUIDIC TECHNOLOGIES

Dimos POULIKAKOS
Laboratory of Thermodynamics in Emerging Technologies
Mechanical and Process Engineering Department
ETH Zurich
dimos.poulikakos@ethz.ch
www.ltnl.ethz.ch

**Abstract** This paper highlights examples of my current research in heat transfer and fluidics at the interface of energy applications and micro- and nanoscale technologies. It is not the scope of this paper to present an exhaustive account of all current and past activities related to its title. It is rather an account of current research in my laboratory in this area, containing both the underlying scientific challenges as well as the hoped final outcome in terms of applications. To this end, examples from the areas of energy conversion, as well as energy transport will be discussed. In the area of energy conversion an original, deformable, direct methanol micro-fuel cell will be presented made of lightweight, flexible, polymer-based materials. A basic understanding and control of two-phase flows (in this case methanol and carbon dioxide) in microchannels as well as novel materials processing and microfabrication methods are directly related to the performance of such energy conversion devices. In the area of energy conservation and reuse, examples from the information technology are employed. Specifically, new concepts of liquid (water) cooling of chips reaching heat removal rates in excess of 700 W/cm2 in domains with restricted heights of the order of one mm will be presented. One additional advantage of using water to cool high density electronics is energy reuse, due to the potentially much higher exergy content of the coolant compared to air cooled technologies. The last part of the paper focuses on the employment of functional nanostructures such as carbon nanotubes and nanowires of conductive and semi-conductive materials for the efficient transport of electricity and heat and the need for the development of novel technologies for the manufacturing, characterization as well as handling of such nanostructures.

**Keywords:** *energy, micro-fuel cells, electronics cooling, nanotechnology, nanoparticles, carbon nanotubes, nanowires*

## 1. Introduction

Energy has emerged as arguably the most important challenge facing humanity in the 21$^{st}$ century This fact has reinvigorated the energy debate and research worldwide, bringing to the forefront the multifaceted nature of the scientific and social problems involved, resulting from a rapidly growing, energy hungry world population. At the outset of the scientific debate and depending on its context, a number of basic facts have to be understood. For the energy-engineering scientist, the following are of paramount importance:

-The issue of *quality* is essential in understanding energy.

-The continuous scientific challenge is the *conversion* of various forms of "lower" quality energy (thermal, chemical, nuclear etc.) to the "highest" quality mechanical-electrical energy.

-Every time we convert we lose in overall quality (2nd Law of Thermodynamics). Hence, we convert as efficiently and as little as possible (conservation) with due respect to the environment.

Thermofluidic engineering is at the center of just about every energy activity, because thermal energy, its production, transfer, harvesting, control, and storage are necessary steps on the way to conversion to electrical or mechanical energy. In addition, thermal energy is often used directly in a large variety of heating and cooling applications, related or not related to conversion or utilization of other forms of energy.

In this lecture I will attempt to give some examples of current heat transfer research as we enter the 21st century that are directly related to the issue of energy as I described it above. At the beginning of the 21st century we are fortunate to have at our disposal tools and technologies, which the pioneers in the field of heat transfer could not even dream about. To this end, the issue of enabling micro- and nanotechnology for energy applications is central to all the topics I will cover in this lecture. Today, we are able, for example, to analyze and control transport of fluids and heat in channels that are not only smaller than the human hair, but they are beyond the realm of continuity, going down to diameters of molecular dimensions. We can investigate and quantify the transport of heat through the interface between two materials from the atomic viewpoint. Such developments create a new perspective and can give birth to new ideas to confront the energy challenge.

The paper and the lecture are structured as follows: Starting with the area of microscale energy conversion, a deformable, direct methanol micro-fuel cell will be presented, made of lightweight, flexible, polymer-based materials. The importance and control of two-phase flows (methanol and carbon dioxide) in the microchannels of the anode of the fuel cell is directly related to the performance of such energy conversion devices. Next, the area of ultra high heat flux cooling in small spaces will be discussed as well as its implications in energy conservation, in particular as it relates to information technology. Specific concepts include optimized, nature-inspired microchannel designs for liquid transport, combined with ultra-high heat flux impinging micro-jet cooling. The last part of the paper focuses on the employment of nanostructures for novel energy applications, such as, carbon nanotubes and nanowires of conductive and semi-conductive materials for the efficient transport of electricity and heat and the need for the development of novel technologies for the characterization as well as handling of such nanostructures.

## 2. Energy Conversion: A Deformable, Direct Methanol Micro-Fuel Cell

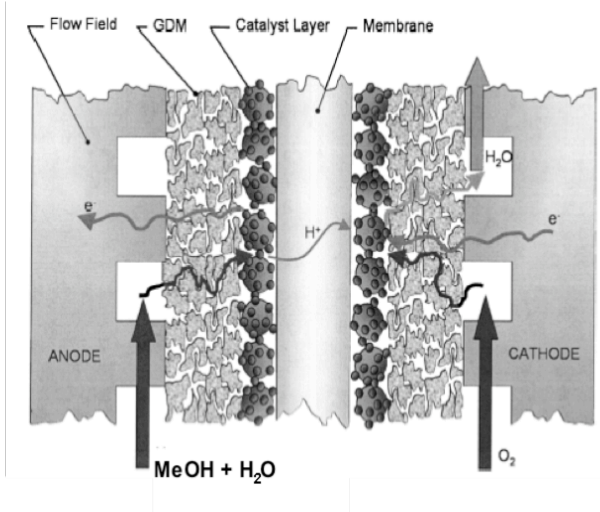



Figure 1. Operating Principle of a direct Methanol Fuel Cell

The schematic in Fig. 1 above shows the operating principle of a direct methanol fuel cell (DMFC). While progress has been made toward the realization of such transportable devices with traditional materials, there is a need for the integration of devices in personal, also wearable environments that are non-flat, undergo deformations and prefer to carry only a limited weight. This gave impetus for the creation of the flexible direct methanol fuel cell shown in Figure 2.

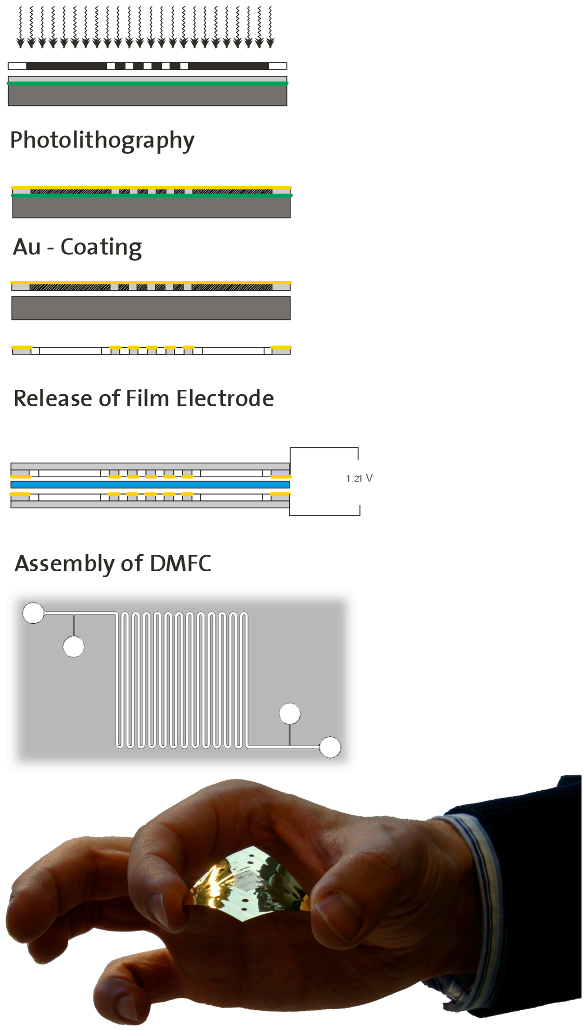



Figure 2. Assembly and photograph of a flexible, small-scale fuel cell on polymer based materials, showing also the serpentine channel geometry for the anode and cathode.

The critical point in the manufacturing of such a device is the combination of metals (gold) and polymers required for the cell anode and cathode see Ref. [1]. A standard microfabrication/MEMS technique [2], based on photolithography was applied to manufacture micro-sized channel networks, see the fabrication steps in Figure 2. In a first step a 500 ± 25 µm thick, p-doped, double side polished, 4" silicon wafer with a resistivity of up to 30 ohm·cm was coated with at 10 µm thick layer of a negative photoresist. In the subsequent photolithographic process step the mask polarity of the deployed high-resolution quartz mask patterns the photoresist during the UV exposure. A dry etching procedure was performed using an inductive coupled plasma system (ICP, Surface Technology Systems) resulting in a rectangular shaped channel cross-section with a depth and width of 200 µm.

The surface roughness of the channel walls is defined by the cycle length of the involved "Bosch process" and the mask resolution, and does not exceed 1 µm. By the iteration of the abovementioned steps at the backside of the silicon wafer, fluid inlets, outlets and pressure ports are incorporated. After dicing the wafer into predefined microchannel chips, PEEK (Upchurch Scientific®) fluid connectors were sealed to the inlet, outlet and pressure tubes by epoxy. After the anode and cathode of the fuel cell were manufactured in the abovementioned manner, they were processed together sandwiching in between a standard polymer electrolyte membrane, on one side of which an appropriate catalyst was layered. An example of the performance of the resulting fuel cell is shown in Fig. 3. The corresponding flow fields in the fuel cell anode microchannels are shown in Fig. 5. The darker areas denote gas regions (carbon dioxide). It is clear that the presence of gas disrupts the electrical performance of the fuel cell and may strongly reduce the produced power (compare Figs. 3 and 4).

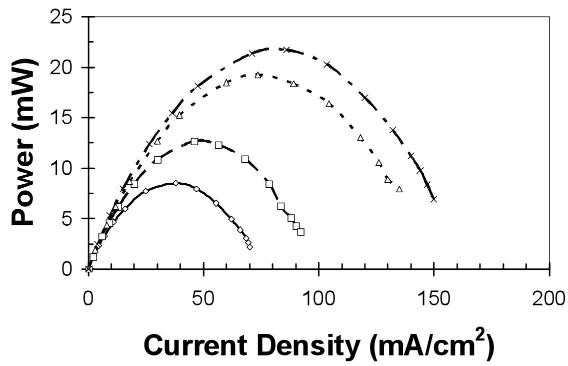
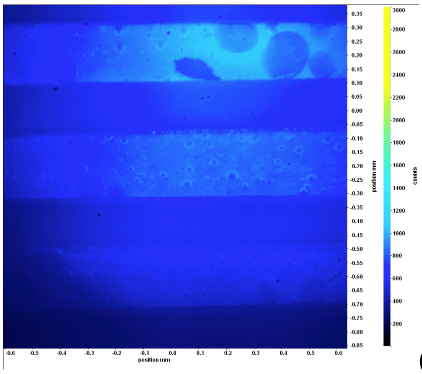
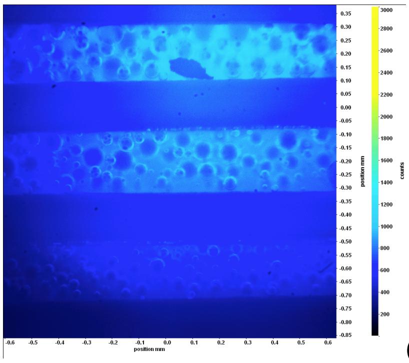



Figure 3. Performance curves of a flexible micro-DMFC



(A)



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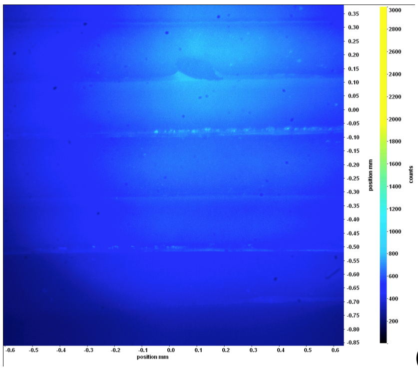

(C)

Figure 4. Flow configurations in the fuel cell microchannels corresponding to the designated curves A, B and C, top, second from top and bottom curves in Figure 4.

## 3. Thermal Energy Transfer: Microchannel Ultra-High Heat Flux Cooling Devices fro Electronics

The past few decades have seen a rapid growth in the computational power of processor chips, which may continue as predicted by Moore's law. The exponential increase in transistor density and storage density as well as the faster clock speed, however, cause serious problems in the thermal management of microelectronic devices. The miniaturization trend renders the thermal management challenging, especially when strict limitation of space and operating costs are applied. Until now the CPUs are cooled using large air heat sinks, but this will not be sufficient for cooling the next generation of microchips [4,5], particularly in compact multichip modules and 3-D microelectronic packages. Hence, novel cooling methods with thin form factors and high cooling performance are needed urgently.

We demonstrated an ultra thin heat sink for electronics, combining optimized impinging slot-jets, micro-channels and manifolds for efficient cooling. The design is optimized for a 2 x 2 $cm^2$ chip and provides a total thermal resistance of 0.087 $cm^2K/W$ for flow rates < 1 l/min and an overall pressure drop < 0.1 bar**.** This results in a maximum cooling capacity of 750 $W/cm^2$ for a temperature difference between fluid inlet and chip of 65K.

No previous studies in the literature considered the influence of the manifold on the hydrodynamic and thermal performance of the heat sink. This simplification is appropriate if there are no size restrictions in the third dimension. With denser packages, there is a demand for thin and efficient heat sinks with only lateral access for fluid supply and return. For these systems the optimum choice of design parameters can only be determined by combined analysis of the performance of a unit cell of the heat transfer structure and the design of the manifold.

We have demonstrated through modeling and experiments, [6,7], that combining heat transfer micro-channels containing slot-jets structures bringing coolant to the hot surface with manifold channels for the coolant transport, allows the optimization of an overall heat sink performance (Figure 5). First, we introduced a three-dimensional model of a unit cell of the heat transfer structure to solve the conjugate heat transfer problem for the micro-channel/jet flow. We then studied the basic physical phenomena of a unit cell and its dependency on the volumetric flow rate. We varied the length, channel width, fin thickness to channel width ratio and inlet/outlet width for a constant volumetric flow rate to determine the sensitivity of the heat sink to the individual design variables. In a second step we constructed a three-dimensional model considering the flow in the manifold channels and the heat transfer structure [6]. This model is applied to study the capability of the manifold to uniformly distribute the liquid coolant and to demonstrate that a design with tapered inlet and expanding outlet manifold channels provides uniform fluid distribution. The model results were confirmed by experiments [7].

The design consists of a manifold system with lateral fluid supply-and-return, which feeds an array of parallel micro-channels where the heat transfer is performed (Figure 5). Fluid enters the inlet manifold channels from the side. Along the inlet manifold channels the flow uniformly branches into the subsequent heat transfer structures through slit nozzles at the bottom wall of the manifold channels. The parallel micro-channels are orthogonal to the manifold channels. Hence, the flow direction after impingement on the hot surface at the bottom of the heat transfer channels is perpendicular to the one of the manifold system. While travelling along the heat transfer micro-channels, the fluid removes the heat, leaves the heat transfer micro-channel structure upwards through slit nozzles and merges into the outlet manifold channels, which guide the fluid to a lateral return (see Figure 5). The entire chip area can be cooled by just one of these systems, comparable from a manufacturing standpoint to a parallel channel network with a lateral manifold system as it was studied in one of our earlier papers [5]. It is possible that many of these systems are arranged in parallel to reduce the overall pressure drop and bulk thermal resistance of the heat sink.

Figure 6a shows streamlines starting from points equally spaced over the inlet surface. The flow enters the heat transfer structure through the inlet nozzle and impinges on the channel bottom wall where it undergoes a 90 deg. change of momentum. The vorticity with its axis transverse to the flow in the streamwise direction generates recirculation near the inner corner at the channel entrance, where the fluid velocity is much slower (Figure 6b). As the fluid flows along the channel, a hydrodynamic boundary layer develops. Towards the end of the channel the fluid is drained to the outlet nozzle with a stagnation zone formed in the channel region opposite to the outlet nozzle.

Figure 6c shows the static pressure contours at the center-plane of the heat transfer unit cell. From this Figure, it becomes obvious that the hydrodynamic performance of the unit cell is dominated by the pressure drop across the inlet and outlet nozzles and not by the pressure drop along the channel.

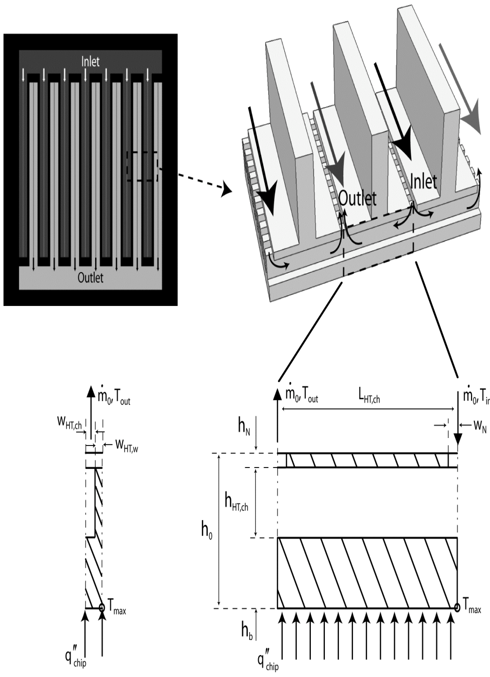


Figure 5. Schematic of a manifold micro-channel heat sink a) top view on manifold, b) isometric section view c) unit cell of the heat transfer structure side view d) unit cell of the heat transfer structure front view, from Ref. [6].

In order to analyze the thermal performance further, we present temperature contours in the solid and the fluid domains at the center-plane of the heat transfer unit cell in Figure 6d. Cold fluid enters the heat transfer structure through the inlet nozzle and impinges on the bottom channel face opposite to the inlet nozzle. The impinging jet inhibits the growth of hydrodynamic and thermal boundary layers, resulting in a small diffusion length from the solid wall to the convective flow and thus in an enhanced heat transfer rate.

Many more details on the performance of this ultra-high heat flux heat sink can be found in [6, 7]. In the following, we compare the efficiency of the different heat sink designs. The efficiency of a heat sink is defined by the ratio of the removed heat flux for a certain invested pumping power. The ability to remove a certain heat flux scales directly with the total thermal resistance of the system. For this reason we compare in Fig. 7 the total thermal resistance of the different designs as a function of idealized pumping power, $P$, which is defined as

$$P = \Delta p \dot{V}_{tot} \qquad (1)$$

In the case of high pumping powers and correspondingly high volumetric flow rates, the design with the smallest channel width of the heat transfer structure namely $w_{\mathrm{HT,ch}}$ = 25 µm performed most efficient, although it had the highest hydrodynamic resistance (Fig. 7).

At a constant pumping power, the volumetric flow rate was lower for the test-vehicle with $w_{\mathrm{HT,ch}}$ = 25 µm than for the other two with larger channels and consequently it provided a higher bulk thermal resistance. However, due to the lower convective thermal resistance of this test-vehicle, the available thermal mass flux was used more efficiently resulting in higher outlet temperatures for a constant heat flux. When the pumping power was reduced, the increase of total thermal resistance of the test-vehicle with $w_{\mathrm{HT,ch}}$ = 25 µm was more pronounced compared to the other two devices.

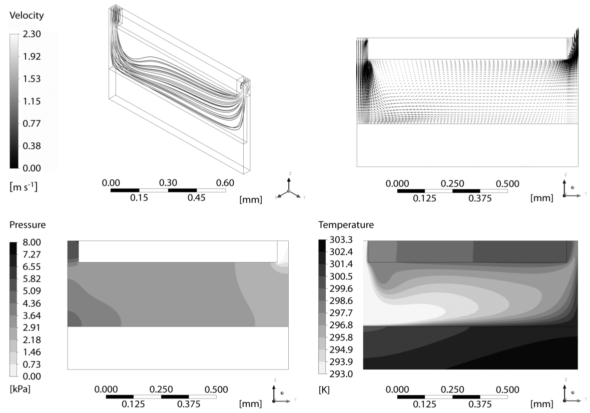


Figure 6: Spatial visualization of basic physical phenomena for a representative case at the center XZ-plane – a) streamlines starting from points being equally distributed over the inlet surface, b) velocity vectors, c) pressure contours and d) temperature contours – computed by means of three-dimensional model of the unit cell of the heat transfer structure, from Ref. [6].

Since its convective thermal resistance was lower than that of the other devices, the transition at which the bulk thermal resistance became the dominant part in the resistance chain occurred at higher volumetric flow rates and, consequently, at higher pumping powers.

In all, the total thermal resistance of the test-vehicle with $w_{\mathrm{HT,ch}}$ = 25 µm showed a stronger dependence on the pumping power. For pumping powers below 0.06 W it would be beneficial to increase the channel width of the heat transfer structure from $w_{\mathrm{HT,ch}}$ = 25 µm to $w_{\mathrm{HT,ch}}$ = 50 µm in order to reduce the hydrodynamic resistance and at the same time the bulk thermal resistance. At this point the increase of the convective thermal resistance due to an enlargement of the channel width would be compensated by the reduction of the bulk thermal resistance [7].

Further, we demonstrated (not shown here for brevity) the potential of the heat sink design to be used in combination with elevated inlet temperatures to reduce the datacenter energy costs and to allow energy reuse. We studied the influence of increased fluid inlet temperatures on the performance of the best performing test-vehicle with a channel width of $w_{HT,ch}$ = 25 µm. An increase of fluid inlet temperature from 20°C to 70°C lowered the pressure drop across the heat sink about 40% due to a 60% reduction of the dynamic viscosity of water.

The pressure drop reduction was not linear as the dynamic viscosity of water decays exponentially with temperature. On the other hand, the total thermal resistance of the heat sink was increased by about 12%, being mainly attributed to a 20% reduction of the silicon's thermal conductivity. A reduction of the thermal conductivity of silicon contributed to an increase of the conduction thermal resistance of the silicon base causing a 6% increase of total thermal resistance [7]. In addition, the fin efficiency was decreased causing a reduction of the convective thermal resistance. On the other hand, the fluid thermal conductivity was increased by about 10% resulting in an increased convective heat transfer. However, the total thermal resistance of the heat sink was only slightly affected by the convective thermal resistance as the latter has only a share of 20% in the chain of thermal resistances. The volumetric heat capacity of the fluid decreased by about 2%, which directly affected the bulk thermal resistance of the system.

## 4. Thermofluidics with Carbon Nanotubes and Nanowires

A very important part of the energy challenge in the 21st century is energy transport in the form of electricity including the related heat transfer issues. Nanotechnology has a lot to offer here, in particular in terms of nanoengineered materials and interfaces between different materials featuring desired properties, far superior to those of bulk materials. To this end, novel characterization methods need to be developed in parallel, for the accurate determination of the properties of such nanomaterials.

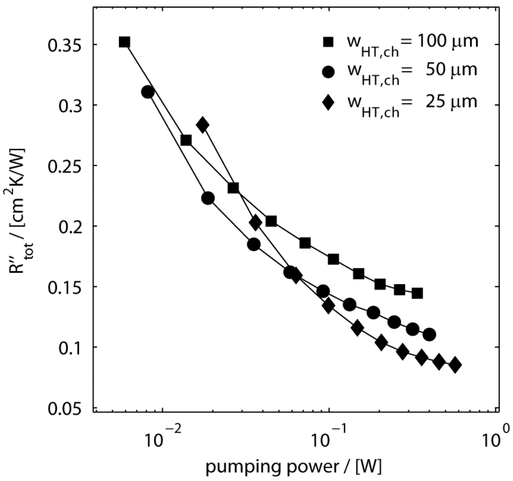


Figure 7. Maximum total thermal resistance as a function of pumping power for varying channel width $w_{HT,ch}$ . From Ref. [7].

In this lecture, I will focus on the topic of determination of the thermal conductivity of a very promising multifunctional kind of nanomaterial, namely, the carbon nanotube [8,9].

Theories and experiments showed that carbon nanotubes have remarkable thermal properties. However, both the experimental data and the theoretical predictions are scattered over 1 order of magnitude. In recent experiments, the reported thermal conductivities for multiwall carbon nanotubes at room temperature are in the range 400- 3000 W/mK, likely depending on the type and size of carbon nanotubes (CNTs) utilized, which give rise to different mean free paths of the energy carriers.

There is still a need for a reliable and reproducible measurement technique to test the theoretical predictions and to provide fundamental thermophysical data for an efficient design of carbon nanotube based nanoelectronics. To fully understand the fundamental heat transport characteristics in the mesoscopic scale, reliable data of thermal conductivity for various sizes of nanotubes should be collected in a reasonably precise manner. To this end, we developed a novel measurement technique based on the four-point-probe third-harmonic (3-$\omega$) method with assistance of a focused ion beam (FIB) source for the fabrication of the needed experimental device [8,9].

We have employed the four-point 3-$\omega$ method for a carbon nanotube. However, the proposed method can be easily implemented to other nanosystems. With this method, the contact resistance was eliminated and spurious signals caused by it could be avoided. Hence, the contact contribution can be neglected in both the electrical and the thermal network. To construct a four-wire connection, a simple nanofabrication process was developed in which FIB milling was performed on a prefabricated microdevice (Fig. 8). The control of individual carbon nanotubes was realized by dielectrophoresis (Fig. 8). By applying a constant amplitude ac current through the carbon nanotube, we could generate a temperature rise fluctuating at the second harmonic and measure the 3-$\omega$ signal, which is used to compute the thermal conductivity. The multiwalled carbon nanotube used in this study shows a dissipative nature. MWCNTs are diffusive conductors. As a consequence, the one-dimensional heat diffusive equation along the nanotube suspended between two metal electrodes can be utilized to obtain a closed form solution of the third harmonic response [8,9].

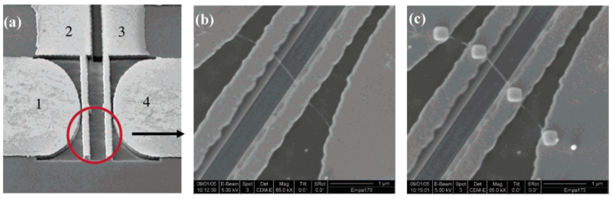


Figure 8. A series of pictures of a four-point-probe 3-$\omega$ experiment: (a) four-wire construction by focused ion beam milling; (b) selective deposition of single CNT by dielectrophoresis; (c) electron beam soldering at four contacts, from Ref. [8].

Finally, a novel approach for the micro-deposition of liquids and nanoparticle colloids on surfaces, or their micro-droplet generation, driven by dielectrophoretic forces, is worth discussing [10] herein. Employing this method, the vertical growth of conductive gold nanowires under ambient conditions by on-demand dielectrophoretically guided deposition of nanoparticle-laden colloids is demonstrated. Gold nanoparticles (3-7 nm) suspended in n-tetradecane leave a metal coated capillary nozzle (borosilicate glass, orifice diameter 500 nm) through dielectrophoretic forces as rapidly evaporating colloidal droplets and are guided through an inhomogeneous electrostatic DC-field. Once deposited on a substrate, the nanoparticles in the colloidal droplets combine under the action of van-der-Waals attraction forces to form highly flexible vertical nanowires. Wires of various lengths up to 20μm and diameters in the range of 150-800 nm are readily grown by this method (Figure 9). The initiation of the deposition process, the wire diameter, and the wire length are controlled by adjusting the global average electric field between the nozzle and the substrate taking advantage of very high electric field gradients at the very end of the nozzle.

Figure 9. A vertical gold nanowire on an electrode, from Ref. [10].

## 6. Closing Remarks

Energy is arguably the most important technical and scientific challenge facing humanity as we enter the 21$^{st}$ century. Significant progress is required in all areas of energy conversion, energy transport and energy storage and conservation. Due to our increasingly mobile society, the capability of decentralized, transportable and personal power generation is becoming a major driver for emerging energy technologies. All the above must be achieved with a great sensitivity to the environmental impact of energy technologies, as the warning signals of the harmful impact of human activities on the environment have reached the danger level. Micro- and Nanotechnologies can significantly contribute to the emergence of the next generation of energy devices in particular through the enabling of manufacturing of devices and materials with superior performance. Examples of such devices and materials were shown in the course of the lecture. Significant advances in experimental heat transfer and the related thermodynamics are central issues in many novel energy applications and in combination with the great potential of nanotechnology, they can surely be a major contributor to overcoming the energy challenge in years to come.

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