Droplet Microfluidics as a Tool for the Generation of Granular Matters and Functional Emulsions†

Adam S. Opalski, Tomasz S. Kaminski and Piotr Garstecki*

1 Institute of Physical Chemistry, Polish Academy of Sciences, Poland

Abstract

Emulsion—a liquid dispersed in another liquid—is in many respects very similar to granular matter. In the early 2000s a new technology—droplet microfluidics—began emerging from the wider field of microfluidics. Droplet microfluidics was quickly established as a discipline of science and engineering and has been used for the generation of highly uniform emulsions. The last few years have brought significant advances to the field, directed towards a wide range of applications in material sciences—from synthesis of nanoparticles in droplets to assembling complex droplets and using droplets as templates for ordered materials, with applications in food, cosmetic and diagnostic industries. Droplet microfluidic platforms are also successfully used as analytical tools in molecular biology and biochemistry, in e.g. high-throughput screening, digital assays, encapsulation of single cells, sequencing technologies, and in point-of-care diagnostic applications. This article provides an accessible overview of the physical phenomena observed in multiphase flow at the microscale and the techniques in droplet microfluidics systems. We also present the most interesting applications and potential further directions of research in this fascinating young field of science and engineering.

Keywords: emulsions, microfabrication, microdroplets, microfluidics, double emulsions, material sciences

1. Introduction

Granular materials are interesting from the physical point of view as they can be considered both as unusual solids and as unusual fluids. For example, despite being large conglomerates of discrete macroscopic particles, granular materials can flow like fluids (Hinrichsen and Wolf, 2004). These materials comprise discrete pieces of solid materials immersed in an interstitial fluid, e.g. air, just like emulsions in which discrete volumes of liquid are dispersed in another liquid (Everett, 1972). Similarly to the physicochemical methods of production of monodisperse particles and granules, microfluidics provides an approach to generate monodisperse functional emulsions—fluidic equivalents of granular materials (Fig. 1). Droplet microfluidics is a young and dynamic field of research that focuses on precise manipulations of microdroplets with volumes ranging from femto- to microliters—i.e. covering the range of three orders of magnitude in the length scale (here measured by the diameter of the droplet) between a micrometer and a millimeter (Leman et al., 2015).

2. General introduction to microfluidics

Microfluidics is an interdisciplinary field of research intersecting engineering, physics, chemistry, nanotechnology, biology and material sciences (Joensson and Andersson Svahn, 2012). Microfluidics studies the properties of fluids at the microscale and develops systems relevant to both academic and industrial applications. Microfluidic techniques are based on the precise handling of small volumes of fluids confined to miniature channels with typical dimensions from one to hundreds of microns. The small dimensions guarantee the laminar flow of liquids and provide for precise control over the transport of fluids (Jeon et al., 2000; Reyes et al., 2002). The channels are usually microfabricated on small polymeric (thermoplastic or elastomer) or glass plates and are typically inexpensive and disposable (Berthier et al., 2012; Unger et al., 2000).

2.1 Single-phase microfluidics

In the first years of the microfluidic era, the research focused only on the single-phase continuous-flow systems which controlled the flow of miscible liquids in the networks of microfluidic channels (Squires and Quake, 2005). In these systems small portions of fluids are delivered to a chip in a specified order and are next mixed and
incubated under various conditions (Sackmann et al., 2014). Flow is usually applied and controlled via the use of pneumatic microvalves (pressure-driven flow), pumps (displacement-driven flow) (Harrison et al., 1993) or with the use of specific physical phenomena such as, e.g. electro-wetting or electrokinetic flow (Persat et al., 2009a, b). The breakthrough point for single-phase microfluidics was development of the microfluidic large-scale integration—a fluidic equivalent of a technology routinely used in the electronic industry that allowed for massive parallelization in the execution of biological assays and chemical reactions in complex microscopic hydraulic architectures (Melin and Quake, 2007; Thorsen et al., 2002).

2.2 Limitations of continuous flow microfluidics

Despite many unique characteristics that led to powerful and robust applications, single-phase microfluidics has limitations. First drawback is the parabolic profile of flow with faster velocity of the fluid at the center of the channel (phenomenon known as Taylor-Aris dispersion) that results in unequal residence times of substrates in single-phase microfluidic reactors (Aris, 1960; Taylor, 1953). Additionally, mixing is slow due to the laminar regime of flow typical at the microscale, and this problem is further amplified in the case of viscous fluids (Casadevall i Solvas and deMello, 2011; Song et al., 2006; Squires and Quake, 2005). Moreover, the solid substrate is in direct contact with the solution and as a consequence, chemical compounds and biological objects (biomacromolecules, proteins, nucleic acids, cells, etc.) can foul the surface of the channel, thus leading to cross-contamination or, in extreme cases, to clogging of the channel (Schneider et al., 2013). And vice versa—bulk material of the chip can release chemical compounds influencing the process in the microfluidic reactor—e.g. monomers of uncured polymer poly(dimethylsiloxane), PDMS, can be toxic for cells growing in a single-phase microfluidic chamber (Regehr et al., 2009).

Another challenge lies in the demanding fabrication of multilayer devices that contain a relatively large number of flow inputs and outputs providing complete control over the transport of the fluid, yet the entire system is characterized by slow actuation of the integrated valves (Thorsen et al., 2002).

3. Droplet microfluidics

3.1 Introduction to droplet microfluidics

Microdroplets possess several unique properties that justify the research on multiphase flows at the microscale and their use as an attractive alternative to the classic macroscale reactors or continuous-flow microfluidic systems. Droplet microfluidics is a technique in which multiple immiscible fluids are confined in microchannels whose size is typically in a range from one to hundreds of micrometers. Discrete volumes of liquids or gases (i.e. droplets or bubbles) are transported, manipulated and investigated in the network of microscopic channels. The common and main function of microfluidic multiphase systems is the generation of highly monodisperse emulsions. Microdroplet emulsions are denoted as water-in-oil (or W/O), if an aqueous phase is dispersed in an organic phase, or oil-in-water (O/W), if the phases are reversed (Xu et al., 2006). There are other combinations of fluids used in microdroplet systems, including i) water-in-water emulsion (Esquena, 2016); ii) oil in another oil, (Klapper et al., 2008) or iii) emulsions that comprise more than two phases (highly ordered emulsions, e.g. double-emulsion W/O/W or O/W/O, triple-emulsion W/O/W/O, etc.) (Abate and Weitz, 2009; Vladisavljević et al., 2017).

Droplets dispersed in the immiscible continuous phase offer the advantage of large numbers of isolated microvolumes—without the need to build solid wall enclosures for each of the microvolumes (Agresti et al., 2010). Spatial isolation of fluidic microcompartments limits the risk of cross-contamination and completely prevents dispersion of the time of residence of analytes in the flow-through system (Temiz et al., 2015). Good heat and mass transfer and fast mixing also occur thanks to the chaotic advection (Gu et al., 2011; Tice et al., 2003, 2004). Microfluidic systems are used to perform typical laboratory operations using a fraction of the volume of the reagents and overall
In a shorter time when compared to batch methods (Teh et al., 2008). The droplet microfluidic systems can be automated and operated at extremely high throughputs of up to thousands of operations per second (e.g. generation or sorting of droplets in the microfluidic device) (Guzowski et al., 2011; Leman et al., 2015; Sciambi and Abate, 2015).

3.2 Basics of physics of microdroplet systems

3.2.1 Surface forces

The fundamental force in the generation and stability of emulsions is that stemming from the energy of interfaces. Liquid molecules are held together by cohesive forces and each molecule is pulled in every direction equally by its neighbors. At the interface between two immiscible fluids, molecules are pulled only by their neighbors from the inside of the droplet, creating additional internal pressure, called Laplace pressure ($\Delta P$). In the equilibrium state, this pressure is balanced by the surface tension—a tendency to curve the interface to minimize the surface area. Balance of forces is described by the Young-LaPlace equation:

$$\Delta P = P_{\text{inside}} - P_{\text{outside}} = \gamma (1/R_1 + 1/R_2)$$  \hspace{1cm} (1)

$\Delta P$—Laplace pressure [Pa];

$P_{\text{inside}}$—pressure inside the curved interface [Pa];

$P_{\text{outside}}$—pressure outside the curved interface [Pa];

$\gamma$—surface tension [J∙m⁻²];

$R_1$ and $R_2$—principal radii of curvature. (Tadros, 2013; de Gennes et al., 2004)

Surface tension plays the critical role in the stability of droplets during their transport and the manipulation of them on a chip (Joensson and Andersson Svahn, 2012). Emulsions are metastable and with time they degrade via the coalescence and Ostwald ripening—a process within which the droplets merge with each other (Leal-Calderon and Poulin, 1999). The lifetime of droplets (and the emulsion) may vary from milliseconds to years depending on the stabilizing characteristics of a surfactant, physical conditions of the environment and the index of polydispersity—i.e. the breadth of the distribution of volumes of the droplets (Baret, 2012). The most common composition of continuous phase used in droplet microfluidics comprises fluorinated liquid and a biocompatible fluorosurfactant which ensures stability of the emulsions (Holzze et al., 2008). For other liquids one must use a suitable surfactant which is often a challenge (Baret, 2012; Holzze et al., 2008).

Novel and promising approaches to stabilizing emulsions are based on the use of nanoparticles in the so-called Pickering emulsions (Pan et al., 2014, 2015), or surfactant-free emulsions (Sakai, 2008). In complex emulsions, such as double emulsions in which the droplets encapsulate yet more droplets in themselves, it is important to use proper sets of additives for each phase (surfactants, osmotic agents) in order to balance all types of forces in the system, including osmotic pressure, Laplace pressure and interfacial forces (Deng et al., 2016; Kanouni et al., 2002; Zinchenko et al., 2014).

3.2.2 Wetting

In droplet microfluidic systems, a phenomenon of utmost importance is wetting, i.e. the ability of the solid surface to maintain contact with a continuous liquid due to molecular interactions (Tarazona, 1987). Wetting can be defined as the function of the surface tension and contact angle between the fluid and the solid and is schematically presented in Fig. 2. In general, for contact angles $\theta < 90^\circ$, wetting of the surface by the liquid is favorable. For contact angles $\theta > 90^\circ$, wetting is unfavorable—fluid minimizes the contact area with solid. When $\theta \sim 90^\circ$, then liquid partially wets the solid substrate and makes the precise control over liquid very challenging, which is highly undesirable in droplet microfluidics. For the droplet microfluidic systems to work reproducibly and controllably, it is a critical requirement that the droplet phase does not wet the walls of the channels and is always separated from these walls by at least a thin wetting film of.
the continuous liquid. In droplet microfluidic systems, wetting of the channel walls by both phases must be perfectly controlled in order for the system to work in a stable and predictable manner. Preferential wetting of the walls by one of the phases determines which phase is the continuous phase (the one that wets walls) and which one will be dispersed (does not wet the walls). W/O emulsions, or any multiple emulsion with oil as the outer phase, are made in hydrophobic devices (Jankowski et al., 2011). O/W or any multiple emulsions with an aqueous outer phase are formed in hydrophilic devices (Derzsi et al., 2011; Jankowski et al., 2013).

### 3.2.3 Capillary number

The capillary number (Ca) is a dimensionless quantity that is used to define the mechanism of droplet formation in each of the following methods of droplet generation: i) in co-axial capillaries (Huang et al., 2014), ii) T-junction (Christopher et al., 2008; De Menech et al., 2008; Garstecki et al., 2006; Van Steijn et al., 2009), iii) flow-focusing junction (Dollet et al., 2008; Garstecki et al., 2005b; Nie et al., 2008) and iv) step-emulsification systems (Hein et al., 2015a, b). Ca represents the ratio of viscous forces versus interfacial tension forces and is defined as

\[
Ca = \frac{\mu U}{\gamma}
\]

\(\mu\) – dynamic viscosity of the fluid [Pa·s];

\(U\) – characteristic velocity of the fluid [m·s\(^{-1}\)];

\(\gamma\) – surface tension [J·m\(^{-2}\)].

For low values of Ca (Ca \(< 10\) \(^{-2}\)), droplet formation is driven by interfacial forces in the so-called squeezing regime (Garstecki et al., 2005b, 2006). The tip of the stream of the droplet phase advances to the junction and blocks the flow of the continuous liquid. The viscous shear exerted by the flow of the continuous liquid is too weak to deform the growing droplet. At the same time, the droplet obstructs the flow of the continuous liquid through the junction and the pressure upstream of the droplet increases and causes squeezing of the neck connecting the growing droplet with the inflow of the droplet phase. This process gradually leads to collapse of the neck of the liquid to be dispersed and release of a discrete volume of the liquid as a droplet. Within the squeezing regime, the volume of the droplet depends predominantly on the ratio of flow velocities of both immiscible phases and does not significantly depend on the viscosities of the liquids or the interfacial tension between them.

The predominating force changes from interfacial to shear stress at higher values of Ca in the dripping regime. During this process, the droplet is formed before the phase to be dispersed fills the cross-section of the micro-channel, which results in much higher droplet formation rates than in the squeezing regime. At very high flow rates of fluids which result in high shear forces and high values of Ca, the droplets are produced in a jetting regime in which an unstable jet of fluid is formed and droplets are pinched-off far downstream of the junction (Utada et al., 2007; Zhu and Wang, 2017).

In some cases, besides Ca, other dimensionless numbers can also be used for the description of the process of droplet formation—e.g. Weber number (We), Péclet number (Pe), and Bond number (Bo). However, their significance in the description of phenomena in microfluidic systems is usually much smaller than the role of Ca (Lagus and Edd, 2013).

### 3.3 Formation of droplets in microfluidic systems

#### 3.3.1 Methods using co-flowing streams of immiscible phases

The formation of droplets is the primary functionality of droplet microfluidic systems. Currently, active microfluidic methods are mostly used for the generation of monodisperse droplets. We define active droplet formation as a process during which the droplets are sheared from the liquid thread by a stream of continuous phase. Such methods are characterized by the use of dedicated geometries for droplet formation, i.e. i) T-junction, introduced in the early 2000s (Thorsen et al., 2001) depicted in Fig. 3A; ii) flow-focusing junction introduced to the planar microfluidic devices by Anna et al. (Anna et al., 2003) shown in Fig. 3B; and iii) co-flowing geometry presented in Fig. 3C (Umbanhowar et al., 2000; Utada et al., 2005). The use of these geometries requires active control of the flow of all the phases, and results in the high-throughput production of droplets. During the active generation of droplets, significant volumes of outer phase liquids are used, in comparison to the volume of dispersed phase, resulting in quite sparse emulsions with a polydispersity index usually below 5% in diameter (Zhu and Wang, 2017; Zinchenko et al., 2014).

#### 3.3.2 Passive methods requiring the flow of only the dispersed phase

Microfluidic techniques exploiting interfacial phenomena rather than forces resulting from the flow of the continuous liquid are called passive methods and comprise microchannel emulsification (Sugiura et al., 2000), membrane emulsification (Spyropoulos et al., 2014), EDGE emulsification (van Dijke et al., 2010), and step emulsification (Dangla et al., 2013). Often they do not even require outer phase flow and yield highly monodisperse droplets (Dutka et al., 2016; Zhu and Wang, 2017). Step emulsification shares roots with microchannel emulsification.
tion and is presented in Fig. 3D together with methods of active droplet formation (Dangla et al., 2013; Kobayashi et al., 2002).

3.3.3 Production of multiple emulsions

A very interesting section of droplet microfluidics is the formation of double emulsions (DE) that are defined as emulsions of complex droplets with an inner immiscible core liquid encapsulated in a liquid shell. The complex structure of the immiscible core and shell is suspended in yet another liquid of continuous phase. The innermost and outermost liquids may be the same fluid, e.g. water. Most commonly, double-emulsion droplets comprise aqueous droplets in an oil shell suspended in an aqueous environment (W/O/W), but emulsions of a higher order and different composition are also known and generated in microfluidic systems (Choi et al., 2016a; Garti, 1997). Ideally, the volume of the middle phase should be as low as possible since a reduction of the shell thickness makes double emulsions more stable against rupture, defined as a coalescence of the core droplet with the outer phase. The rupture of the double droplet occurs when the inner droplet moves towards the outer interface of the shell and breaks it. The hydrodynamic resistance that impedes movement of the inner droplet increases with the reduction in shell thickness—for sufficiently thin shells the hydrodynamic resistance allows only marginal fluid flows (Kim et al., 2011; Vian et al., 2016). Currently, the most advanced direct method of single-core DE production reports a 2.5-μm-thick shell in droplets 50 μm in diameter. The thickness of the shell can be further reduced by post-processing to submicron dimensions, i.e. squeezing the double emulsion through the narrow slit that causes the multiple emulsion to lose some shell volume (Akamatsu et al., 2015; Arriaga et al., 2015; Vian et al., 2016) or by dewetting of the shell phase which may lead to the formation of polymerosomes (Deng et al., 2016; Ho et al., 2008; Kim et al., 2013).

Microfluidic systems for the generation of multiple droplets are similar to those used for the formation of single emulsions—they utilize one droplet generation junction located in proximity to another junction. Usually, systems for DE generation require chemical treatment of the surface to adjust the wettability of the channel walls (Abate et al., 2011). Fig. 4 depicts selected and the most common methods for the generation of DE in microfluidic channels. For more information on double emulsion generation, the reader is encouraged to study excellent reviews on the subject (Chong et al., 2015; Vladisavljević et al., 2017; Zhu and Wang, 2017).

All the actively controlled methods provide users with a high degree of control over the process of formation and over the structure of double emulsions, comprising droplets either with single or with multiple cores. The microfluidic methods are truly unique in providing the ability to tune the volumes and number of the cores in multiple droplets. The methods shown in Fig. 4A and 4B share the principle that at first an aqueous droplet is generated in oil in a hydrophobic junction. Next the droplet is transported within an oil thread to another junction of different (hydrophilic) wetting properties where a second aqueous phase shears off the (W/O) single droplet to form a double (W/O/W) droplet (Nisisako et al., 2005; Yan et al., 2013). The mechanism is different in the case of the liquids flowing co-axially in a glass capillary where the DE formation occurs in a single step (Fig. 4C). The device comprises two cylindrical glass capillary tubes nested within yet another glass capillary. The inner fluid is pumped through a tapered cylindrical capillary tube, and the middle fluid is...
pumped through the outer coaxial region. Both fluids form a coaxial flow at the exit of the tapered tube where they meet the outermost fluid, supplied from the other direction through the outer coaxial region. As there is only one outlet from the device, all fluids are forced to flow through the exit orifice where they are hydrodynamically focused into a co-axial thread that eventually ruptures to form multiple droplets (Choi et al., 2016b; Utada et al., 2005).

Methods for the formation of double emulsions are considered passive ones if just the final emulsification step is passive. Firstly, the feed (single emulsion) is generated. Then, the single emulsion is passively split by an outer fluid to form a double emulsion. Passive processes provide a smaller degree of control over the droplet formation, because the operations are hard-wired into the geometries of the devices. Droplet formation also depends on the parameters of used fluids, however, to a smaller extent than on the geometry (Chong et al., 2015; Van Der Graaf et al., 2005). A first system for passive encapsulation of the precisely controlled number of cores inside a double-emulsion droplet has been shown just recently—the single emulsion is used as the feed. Core diameters in the feed emulsion are much smaller than the resultant double emulsions (Eggersdorfer et al., 2017). Fig. 4 shows two systems for passive emulsification techniques: i) an approach by Eggersdorfer who developed the so-called ‘millipede’ device where multiple step-emulsification nozzles operate in parallel (Fig. 4E) (Eggersdorfer et al., 2017), and ii) a system by Sugiura et al., where the single emulsion is extruded from the microchannel through the orifices in the silicone membrane to the outer phase (Fig. 4D) (Sugiura et al., 2004).

An interesting method for the formation of a double emulsion utilizes automated droplet microfluidic systems. Such systems combine active and passive methods of droplet formation, enabling the custom tailoring of multiple droplets one by one (Guzowski et al., 2013). The system allows the formation of multiple emulsions that differ in many aspects—from the number of core droplets, the volume fractions (ratio of volume of inner droplet to the outer shell) to the shape of the formed multi-compartment system (Guzowski and Garstecki, 2015; Guzowski et al., 2012, 2013).

In automated microfluidic systems, the operator can use externally controlled valves to program the protocol to be executed, e.g. a sequence of single emulsion droplets to be produced at the first T-junction and then transported to the step at the entrance to the deep reservoir where it becomes engulfed passively in the outer phase—see Fig. 5A (Guzowski and Garstecki, 2015; Guzowski et al.,

Fig. 4 Schematics of microfluidic technologies for the generation of double emulsions. A–C show methods in which the outer phase flow is controlled, D and E depict methods without the control over the outer phase. A—two consecutive T-junctions. Adapted from (Nisisako et al., 2005) with permission from The Royal Society of Chemistry; B—two consecutive flow-focusing junctions (Yan et al., 2013); C—co-axial microcapillary device that forms double emulsions—from (Utada et al., 2005). Reprinted with permission from AAAS; D—microchannel emulsification of a single emulsion into a double emulsion (Sugiura et al., 2004). The image was created exclusively for the purpose of this review. E—a single emulsion fed into a step-emulsification module to produce a double emulsion. Adapted from (Eggersdorfer et al., 2017) with permission of The Royal Society of Chemistry.
2012, 2013). Automated systems for the production of double emulsions offer precise control over the size and composition of complex droplets in multiple emulsions, as well as their shape and packing of the core droplets—see Fig. 5B–5D. The automated droplet microfluidic system allows tailored single-core double emulsions (Fig. 5B) to be obtained, as well as long, multi-compartment chains, stabilized by capillary bridges between the core droplets (Fig. 5C). Inner cores can be packed in a number of ways depending on the number of cores and their volume fraction, as presented in Fig. 5D (Guzowski and Garstecki, 2015).

3.4 Operations on droplets

The versatility of the droplet microfluidic techniques stems from the ability to first generate and then manipulate droplets on a chip. The droplets can be transported through the network of microchannels and then they can be merged, split, incubated, sorted and the outcome of the reaction can be detected using optical, electrochemical or other analytical methods (Haeberle et al., 2012). Each of the operations can be performed in a dedicated module—a building block of the whole microfluidic system, and these modules can be arranged to form complex devices with many functionalities integrated into a single microfluidic chip (Mair et al., 2017; Schuler et al., 2016).

4. Fabrication of the microfluidic devices for the production of microdroplets

4.1 Prototyping methods

Droplet microfluidic devices can be microfabricated from various materials, e.g. glass, elastomers, thermoplastics, metal, silicone or hybrids of glass and polymer. The choice of the material for fabrication of the chip depends on numerous factors such as: application, cost, material properties and feasibility of fabrication. Some of the most popular methods of prototyping are multi-layer soft lithography, etching, CNC milling, pulling glass capillaries and 3D printing of the microfluidic devices (Jeong et al., 2016).

Microchannels in glass and silicone plates can be fabricated using the deep reactive ion etching (DRIE) technique. The plate must be protected from etching everywhere except for the area of the desired pattern of channels, e.g. by Ni-electroplating or photore sist deposition. Bonding two glass plates with etched features requires a very precise alignment and this process is technically challenging (Harrison et al., 1993; Nisisako and Torii, 2008). Nowadays, glass or silicone plate microfluidic chips are rarely used. Other types of glass devices such as coaxially nested glass capillaries are very common for the production of multiple emulsions (Utada et al., 2005; Zhao et al., 2016). Poly(dimethylsiloxane), usually referred as PDMS, is a material that offers many advantages: it can be used for the reproduction of micron-sized features by replica molding, it is transparent to visible light, it cures at low
temperature, it is non-toxic, biocompatible and gas-permeable, and its surface can be easily modified (Duffy et al., 1998; McDonald and Whitesides, 2002; McDonald et al., 2000). PDMS is a perfect material to complement lithographic techniques and gives a name to ‘soft’ lithography, and the elements of devices made of this elastomer can be easily bonded to one another and to a range of other materials, most importantly to glass, after activation of the surface, e.g. with oxygen plasma or corona discharge (Haubert et al., 2006). Soft lithography enables the monolithic fabrication of fluidic components within one piece of PDMS (e.g. inlets, outlets, connectors, valves, mixers), allowing large-scale integration of the microfluidic circuits (Nisisako and Torii, 2008; Thorsen et al., 2002). Poly(dimethylsiloxane) is highly biocompatible, gas-permeable, is an easy-to-work-with material and is the perfect choice for the fabrication of microfluidic devices for biomedical and biological experiments (Zhou et al., 2010). However, PDMS has some disadvantages such as low chemical compatibility—most importantly this material is not well suited to working with organic solvents as they swell the elastomer and the dimensions of the channels may be significantly distorted (Seemann et al., 2012).

A breakthrough in prototyping was the development of soft lithography by Xia and Whitesides presented in Fig. 6 (Xia and Whitesides, 1998). In common microfabrication protocols, photoresist (e.g. SU-8) is first spin-coated on a glass or silicone slide and then exposed through a mask with a pattern of channels. The exposed resin hardens and the non-exposed photoresist is subsequently washed away. Such a master of the microfluidic device is chemically protected by the deposition of fluorosilanes. Liquid non-polymerized elastomer (PDMS with the curing agent) can be poured onto the matrix, cross-linked by baking at elevated temperatures and peeled off—yielding a perfect negative replica of the silicone-photoresist master. Such an elastomer element cast can then be used as a ready-made part of a microfluidic device and bonded to a glass slide or piece of solid PDMS by activating the surface with plasma. Aligning and bonding two or more layers of patterned PDMS is widely used and is known as multilayer soft lithography. The PDMS cast can be utilized in an alternative way: a chemically protected PDMS cast (by the deposition of fluorosilanes) can be used as a master for the further casting of PDMS. This allows limiting the use of fragile silicon wafers and speeds up the prototyping process, as many such masters can be prepared within a day while microfabricating photoresist on silicone is time-consuming.

Many thermoplastic materials are more rigid than PDMS and they are more robust in terms of mass production. Thermoplastics are also characterized by moderate thermal and chemical compatibility properties, e.g. inferior to properties of glass, but still acceptable for many applications (Jeong et al., 2016). The most common thermoplastics used for the fabrication of microfluidic chips are the following materials: polycarbonate (PC) (Ogończyk et al., 2010), polymethylmethacrylate (PMMA) (Conchouso et al., 2014), cyclic-olefin copolymers (COC) (Stachowiak et al., 2007), polystyrene (PS) (Li et al., 2012), polytetrafluoroethylene (PTFE, also known under the brand name Teflon®), fluorinated ethylene propylene (FEP) (Horka et al., 2016). Prototyping in thermoplastics is usually done by i) micromilling the channels in the plate and bonding it to another plate (Ogończyk et al., 2010); or by ii) 3D printing the appropriate polymer, e.g. methacrylate-based photoresist, in the shape of the microfluidic device (Femmer et al., 2015). These prototyping methods are fast, inexpensive and reliable, but fail to deliver large batches of microfluidic chips. For the mass production of thermoplastic devices, other methods are used, mainly injection molding and hot embossing (Jeong et al., 2016).

4.2 Surface chemistry

In order to maintain precise control over the transport of fluids in the microfluidic chip, the walls of channels have to be preferentially wet by the continuous phase and at the same time the droplet phase should be repelled (Derzsi et al., 2011). Some materials have intrinsically de-

---

1. Perform photolithography
2. Pour PDMS over master and cure
3. Peel PDMS from the master
4. Seal against a flat surface
5. Microchannel is complete
6. Channels may be chemically modified

**Fig. 6** Schematics presenting consecutive steps in a common soft lithography procedure. Adapted with permission from (McDonald and Whitesides 2002). Copyright 2002 American Chemical Society.
PDMS hydrophilic (Filla et al., 2011; Kim et al., 2015). Dizise the surface, rendering the natively hydrophobic processes bombard the exposed PDMS surface and oxidation—ionized oxygen species produced in those fluidic channel network with oxygen plasma or corona discharge. The device can be patterned by treating parts of the microchannels with a glass-like layer with tunable properties (Abate et al., 2010b). Alternatively, modification by acrylic monomer that can bind to the desired regions of the channel network, e.g. hydrophilic surface, e.g. flowing a modifying solution only to the desired areas of the microfluidic network. This makes it possible to define hydrophilic and hydrophobic areas of the microfluidic network. To make PDMS hydrophilic, a sol-gel method is frequently used. It relies on coating the PDMS and glass channels with a glass-like layer with tunable properties (Abate et al., 2008). Other methods are based on the deposition of hydrophobic (or fluoropholic) compounds on the surface of the channels via injection of a solution to the microchannel and evaporation of the solvent (Zuchowska et al., 2016). Easy and durable methods for the modification of the microchannels in PDMS and hybrid PDMS glass devices are available. We can divide the methods into two categories: i) hydrophobic modification and ii) making the surface of channels more hydrophilic.

To make PDMS hydrophobic, a sol-gel method is frequently used. It relies on coating the PDMS and glass channels with a glass-like layer with tunable properties (Abate et al., 2008). Other methods are based on the deposition of hydrophobic (or fluoropholic) compounds on the surface of the channels due to activation of the surface by oxygen plasma or corona discharge, the PDMS surface is rendered hydrophilic due to activation of the PDMS by oxygen plasma or corona discharge—ionized oxygen species produced in those fluidic channel network with oxygen plasma or corona discharge—ionized oxygen species produced in those processes bombard the exposed PDMS surface and oxidize the surface, rendering the natively hydrophobic PDMS hydrophilic (Filla et al., 2011; Kim et al., 2015). Other materials used in microfluidics such as thermoplastics (polycarbonate, PMMA or COC) can have their surface modified. Surface activation with, e.g. ionized oxygen species renders such polymers temporarily hydrophilic—after some time, the surface regains its original properties (Jokinen et al., 2012). To modify the thermoplastics permanently, the surface needs to be physically or chemically modified by, e.g. the layer-by-layer deposition of the polyanions and polycations on a polycarbonate (Derzsi et al., 2011), coating polycarbonate with either a hydrophilic or hydrophobic compound (Jankowski and Garstecki, 2016; Jankowski et al., 2012, 2013), sequential photografting of poly(ethylene glycol) on COC (Stachowiak et al., 2007), or by deposition of silica nanoparticles on PMMA (Ortiz et al., 2017).

5. Applications of droplet microfluidics

Droplet microfluidics is a perfect approach for executing simple protocols that involve handling a large number of small liquid microreactors. This feature makes the microdroplet technology extremely useful for biological applications including the high-throughput investigation of single cells and droplet digital polymerase chain reactions (ddPCR) (Agresti et al., 2010; Baker, 2012; Duncombe et al., 2015; Hindson et al., 2011; Rakszewska et al., 2014; Zinchenko et al., 2014). Droplet microfluidics is also useful for drug research (Sackmann et al., 2014; Vladisavljević et al., 2013), food industry (Neethirajan et al., 2011; Ushikubo et al., 2014; Zanatta et al., 2017), and material sciences for the synthesis and investigation of micro- and nanomaterials such as, e.g. quantum dots, polymeric and inorganic microparticles, capsules (Herranz-Blanco et al., 2014; Vannoy et al., 2011; Zhang L. et al., 2015).

5.1 Chemistry in droplets

The excellent heat and mass transfer in droplets is exploited in the performance of various organic chemistry reactions in microfluidic devices (Kreutzer et al., 2005; Sobieszuk and Napieralska, 2016). For many reactions, the yield is directly associated with the degree of mixing, and microchannel patterns provide the means for the rapid and controllable mixing of content of droplets (de Mello, 2006; Tice et al., 2003). There are also applications of microdroplets in green chemistry—energy consumption may be reduced compared to bulk synthesis (Pieber and Kappe, 2013), and a higher selectivity of reactions allows easier product clean-up (Wiles et al., 2006).

Microfluidic devices offer the capability of performing a wide range of reactions in droplets, e.g. catalysis using the Suzuki-Miyaura reaction (Theberge et al., 2009), hydrolysis of p-nitrotoluene (Ahmed et al., 2006), bromination of alkenes (Cygan et al., 2005), deacetylation of ouabain
hexaacetate (Ac$_6$-OUA) (Hatakeyama et al., 2006) or synthesis of benzyl phenyl ester using PTC (Phase Transfer Catalysts) (Ji et al., 2012). Additionally, reactions at the microscale are safer since smaller volumes of dangerous and explosive substrates can be used, e.g. elemental fluorine for direct regioselective fluorination (Chambers et al., 2005), or preparation of radiolabeled probes (Lee et al., 2005). The high-throughput and spatial separation of samples make droplet microfluidics perfectly suitable for discovery chemistry—screening the libraries of compounds in search of, e.g. new catalysts (Goodell et al., 2009; Kreutz et al., 2010). Droplet microfluidics is also a perfect tool to investigate the chemical communication of compartments comprising chemical oscillators such as the Belousov-Zhabotinsky reaction (Guzowski et al., 2016). An excellent overview of the various reactions performed in microdroplets can be found in a review by Elvira (Elvira et al., 2013) as well as in more recent publications (Guardingo et al., 2016; Wleklinski et al., 2016).

### 5.2 Synthesis of nano- and microparticles

A wide range of nanoparticles (NPs) and microparticles can be synthesized and generated in microfluidic devices, including but not being limited to: metallic NPs, e.g. gold (Duraiswamy and Khan, 2009, Sebastian Cabeza et al., 2012), silver (Xu et al., 2016), core-shell NPs (Zhu and Guo, 2016), Janus microparticles (Maeda et al., 2012; Nisisako 2016), polymer microcapsules and microspheres (Chuah et al., 2009; Ekanem et al., 2017; He et al., 2011; Kumacheva and Garstecki, 2011a, b; Sugiura et al., 2001; Thiele and Seiffert, 2011), semiconductor NPs including quantum dots (Lignos et al., 2014; Vannoy et al., 2011), and silica NPs (Shirk et al., 2013; Wacker et al., 2012).

**Fig. 7** shows an exemplary synthesis of quantum dots in the droplet microfluidic set-up. Double emulsions allow easy and efficient synthesis of capsules and beads, including particles carrying bioactive ingredients (Datta et al., 2014; Deng et al., 2016; Deshpande et al., 2016; Kim et al., 2011). Double emulsions can be efficiently combined with the technique of polymerization of the outer liquid layer in order to obtain various solid shells filled with desired compounds (Wang et al., 2013). DEs with thin shells are the most desirable in the process of fabrication of microcapsules (Datta et al., 2014). The polymerizing agent can be suspended in the shell yielding liquid drops with the solid shell. However, thick shells allow core droplets for movement within the shell so they are off center. After polymerization of such DEs, the shell thickness is not homogeneous and may hamper, e.g. control over the release kinetics of encapsulants (Datta et al., 2012). Thin oil shells may also serve as sacrificial templates for the production of aqueous-based microgels suspended in water—they can spontaneously de-wet upon polymerization of the core droplet (e.g. UV-initiated) to transfer freshly prepared microgels directly into the aqueous solution (Choi et al., 2016b). Another interesting feature of the thin-shelled DEs is that they can be stable until triggered. This unique feature enabled use of DEs in the controlled release of small hydrophilic molecules and can be developed for controlled drug application (Zhao et al., 2016).

### 5.3 Crystallization in droplets

One of the main applications of droplet microfluidics were the studies of crystallization processes, especially protein crystallization. Since there are no universal conditions for the crystallization of proteins or microparticles—the optimum parameters need to be found in multidimensional chemical space (e.g. pH, crystallizing agents, temperature) (Li and Ismagilov, 2010). Droplet microfluidics offers great control over heat and mass transfer and low sample volumes, providing at the same time the possibility executing high-throughput experiments. The synergy of these advantages resulted in development of systems that allow the automated determination of solubility dia-
Detection systems could sight into nucleation and growth processes (Leng and Salmon, 2009; Shi et al., 2017). The research group of Andrew deMello focused on the monitoring of crystallization phenomena of various particles, with special emphasis on nanocrystals (Hatakeyama et al., 2006; Li and Ismagilov, 2010; Zheng et al., 2011; Yamaguchi et al., 2013). The research of Ostwald Ripening (Lignos et al., 2015). High-throughput droplet crystallization assays were developed to work with small volumes, which is invaluable for researchers working with precious materials or samples that are difficult to obtain. In particular, Rustem Ismagilov’s group has been active in investigating and optimizing protein crystallization in nanoliter droplets (Hatakeyama et al., 2006; Li and Ismagilov, 2010; Zheng et al., 2003). The research group of Andrew deMello focused on the monitoring of crystallization phenomena of various particles, with special emphasis on nanocrystals (Lignos et al., 2015; Macieczyk et al., 2016). An example of such research is the time-resolved measurement of the nucleation and growth of PbS crystals in droplets that enabled elucidation of the kinetics of colloid crystallization. Analysis of the kinetics indicated that there are two steps during the early stage of the reaction: in a first step (< 1 second), the nucleation of uniform particles occurs, and in the second one, the particles grow while their concentration decreases, which is consistent with the kinetic model of Ostwald Ripening (Lignos et al., 2015).

Crystals may have many forms characterized by polymorphism expressed by different physical, chemical and biological properties (Braga et al., 2009; Leng and Salmon, 2009). Differentiating between the polymorphs is crucial, especially for the pharmaceuticals industry—a chemical compound may exist in multiple possible crystalline structures, directly influencing the quality of the drug (Mangin et al., 2009). Droplet microfluidic methods allow partitioning the crystallization assay into the small volume of droplets, which may result in the encapsulation of a single crystal nucleus per droplet. As the nucleation process is stochastic, various forms can nucleate in neighboring droplets. With no competition from other nuclei, even highly unstable forms can persist and grow inside the droplet, yielding mononuclear crystals (Shi et al., 2017). Hence, droplet microfluidics allows, e.g. the screening of mononuclear crystals in order to find the most thermodynamically stable form of an active pharmaceutical ingredient. Consequently, the optimization of the crystallization conditions in droplets could be used for obtaining the desired polymorph (Leon et al., 2015; Wang et al., 2011; Yamaguchi et al., 2013).

5.4 Biological and biochemical assays in high throughput

A number of biological assays can be performed using droplet microfluidic chips. The methods for spatiotemporal control over the droplet position on a chip or the techniques for droplet barcoding (Macosko et al., 2015; Rotem et al., 2015; Zhang Y. et al., 2015) offer a way to link the outcome of the reaction with the chemical composition of a droplet (Abate et al., 2010a; Amselem et al., 2016; Jakiela et al., 2013). Well-developed methods for culturing bacteria and eukaryotic cells (Clausell-Tormos et al., 2008; Jakiela et al., 2013; Moffitt et al., 2012), allowed for rapid investigation on the level of single cells. Assays detecting single biomolecules (Hughes et al., 2004; Rissin et al., 2010; Shim et al., 2013) can be performed at a very high throughput (Agresti et al., 2010; Cheng et al., 2016; Lim and Abate, 2013; Lim et al., 2015; Terekhov et al., 2017).

Droplet microfluidics offers an astonishing number of applications in molecular biology, biochemistry, drug discovery, and cancer research. Here, we will mention just a few of the important achievements of droplet research in these fields: i) digitized diagnostic assays (Hindson et al., 2011; Rissin et al., 2010; Tang and Shum, 2016); ii) directed evolution towards the improvement of the catalytic functions of enzymes and microorganisms (Fischlechner et al., 2014; Levin and Aharoni, 2012; Zinchenko et al., 2014); iii) determination of optimum conditions for protein crystallization (Yamaguchi et al., 2013; Zheng et al., 2003; Zhu and Fang, 2013); iv) new experimental approaches useful in the next-generation sequencing of cell genomes (Ma et al., 2017; Macosko et al., 2015; Zhang Y. et al., 2015) offer a way to link the outcome of the reaction with the chemical composition of a droplet (Macosko et al., 2015; Rotem et al., 2015), allowed for rapid investigation (Agresti et al., 2010; Cheng et al., 2016; Lim and Abate, 2013; Lim et al., 2015; Terekhov et al., 2017).

5.5 Industrial applications

Microfluidic methods allow the production of emulsions that are highly monodisperse, with precisely determined diameters of the droplets, and tailored chemical composition of the interface. All these features allow tuning the emulsions for a particular application, yet the microfluidic methods are characterized by intrinsically low volumetric throughput, limiting their applicability (Amstad et al., 2016). Several attempts for parallelization to increase the throughput of the generation of droplets have been reported, e.g.: i) 144 T-junctions in an annular chip (Nisisako et al., 2012); ii) up to 512 flow-focusing junctions in a multilayer annular device, yielding up to a liter of emulsion per hour (ca. 200 µm in diameter, CV~6 %); iii) 28 flow-focusing junctions producing monodisperse droplets up to 3 l/h (ca. 500 µm in diameter); iv) parallel system comprising over 500 step-emulsification junctions to produce up to 150 ml/h of emulsion (ca. 20–160 µm in diam-
Droplet microfluidics has already come a long way since the first demonstration of the formation of droplets on a planar microfluidic chip (Thorsen et al., 2001). Hundreds of researchers across the globe solved a diverse set of challenges and problems, especially in microfabrication, choice of materials and reagents and in the physics of multiphase flow at the microscale.

The progress in droplet microfluidics has also led to academic demonstrations of applications that could open new technological possibilities in such areas as:

i) **analytical sciences and diagnostics**, e.g. by providing users with an array of novel and unique assays such as digital PCR or single-cell sequencing (Hatch et al., 2011; Lan et al., 2017).

ii) **pharmacology**, e.g. by introducing novel methods of drug delivery using microcapsules formed with the use of microdroplets, and the highly selective synthesis of polymorphs of active pharmaceutical ingredients (Leon et al., 2015; Vladisavljević et al., 2013).

iii) **fluid mechanics**, e.g. by investigating the fundamental properties of fluid flow at the microscale (Garstecki et al., 2005a; Nabavi et al., 2015).

iv) **material sciences**, e.g. by overcoming the slow or non-uniform heat and mass transfer in chemical reactions (Song et al., 2006), developing new methods for the generation of highly monodisperse microparticles, capsules (Ekanem et al., 2017; Wang et al., 2011), and porous materials (Thurgood et al., 2017).

The highest impact, at least up till now, has been in biological sciences, listed very briefly in the previous section. Droplet microfluidics helps with detecting medical disorders and microfluidic technologies are already found in diagnostic systems for the detection of infectious, genetic and degenerative diseases. The most important applications of droplet microfluidic technologies comprise the analysis of rare mutations associated with cancer (Pekin et al., 2011), detection of circulating tumor DNA (Garrigou et al., 2016), health monitoring after organ transplantation (Goh et al., 2017) and detection and quantification of pathogenic bacteria (Kang et al., 2014). As the basic physics behind microscale multiphase flows is already well known and the microfabrication techniques are at the level at which it is feasible to mass-produce inexpensive cartridges, we can expect further development of droplet microfluidic technologies for even more complex applications in biological research and medical diagnostics.

Droplet microfluidics is also used in synthetic and physical chemistry. The use of microdroplet reactors will be helpful in the optimization of reactions conditions (Abolhasani et al., 2015a, c) and determination of selected important properties of chemical compounds such as partitions coefficients (Abolhasani et al., 2015b). Droplet microfluidics can be useful in specific applications, as e.g. controlled synthesis at the liquid-liquid interface. The limited volume of the droplet microreactors restricts their use in the classic and large-scale synthesis of common chemical compounds. The situation is different in the case of synthesis and formulation of fine and expensive chemicals such as nanocrystals and microcapsules for which droplet microfluidic have already proved to be a very promising alternative to classic technologies (Ekanem et al., 2017; Nightingale et al., 2014; Phillips et al., 2014). Further studies on the crystallization will be carried out and they might reflect on the fundamental knowledge—e.g. deeper understanding of the nucleation process—as well as on the pharmaceuticals industry—e.g. reduction of time needed for the development of novel drugs by al-
leading early-stage screening of minimal amounts of crystals and co-crystals (Shi et al., 2017).

Microfluidics is still a rapidly developing field of research. The interest has slowly been shifting from the methods for droplet production or manipulation to the development of new applications of already known droplet microfluidic techniques and systems that now allow for high-throughput investigation on biological and chemical processes. High-throughput screening using droplet techniques can identify the most efficient reaction conditions, properties of materials, strains or variants of enzymes that can later be used either by microfluidic or bulk methods.

In terms of generation of new types of capsules, particles and materials for practical applications, currently the biggest challenge is to scale up the production rate, at least on the level of kilograms of materials per hour. This can be realized either by massive parallelization and/or by using new types of devices capable of sustaining very high pressures. We envisage that the current extensive research efforts will lead to substantial improvement and dissemination of droplet microfluidics which will become an important and widely known approach in the research of powders and microparticles.

Acknowledgements

This work was supported by the National Science Centre funding based on decisions number: DEC-2016/23/N/ ST4/01020 (Preludium) and DEC-2014/12/W/NZ6/00454 (Symfonia) and the Foundation for Polish Science through the program TEAM TECH/2016-2/10. T.S.K. acknowledges the support from the Ministry of Science and Higher Education through the scholarship for outstanding young researchers (0722/E-64/STYP/10/295).

References


Abolhasani M., Bruno N.C., Jensen K.F., Oscillatory three-phase flow reactor for studies of bi-phasic catalytic reactions, Chemical Communications, 51 (2015a) 8916–8919. DOI: 10.1039/C5CC02051D

Abolhasani M., Coley C.W., Jensen K.F., Multiphase oscillatory flow strategy for in situ measurement and screening of partition coefficients, Analytical Chemistry, 87 (2015b) 11130–11136. DOI: 10.1021/acs.analchem.5b03311

Abolhasani M., Coley C.W., Xie L., Chen O., Bavendi M.G., Jensen K.F., Oscillatory microprocessor for growth and in situ characterization of semiconductor nanocrystals, Chemistry of Materials, 27 (2015c) 6131–6138. DOI: 10.1021/acs.chemmate.5b02821


Christopher G.F., Noharuddin N.N., Taylor J.A., Nanna S.L., Affordable double-emulsion droplets and their biomedical applications, Microfluidics and Nanofluidics, 7 (2016) 10447–10447. DOI: 10.1038/ncomms10447
Depshande S., Caspi Y., Meijering A.E.C., Dekker C., Octanol-assisted liposome assembly on chip, Nature Communications, 7 (2016) 10447–10447. DOI: 10.1038/ncomms10447
Dutka F., Opalski A.S., Garstecki P., Nano-liter droplet libraries

63


Everett D.H., Manual of symbols and terminology for physicochemical quantities and units, Appendix II: definitions, terminology and symbols in colloid and surface chemistry, Pure and Applied Chemistry, 31 (1972) 577–638. DOI: 10.1351/pac197231040577


Filla L.A., Kirkpatrick D.C., Martin R.S., Use of a corona discharge to selectively pattern a hydrophilic/hydrophobic interface for integrating segmented flow with microchip electrophoresis and electrochemical detection, Analytical Chemistry, 83 (2011) 5996–6003. DOI: 10.1021/ac201007s


Goh S.K., Muralidharan V., Christophi C., Do H., Dobrovic A., Probe-free digital PCR quantitative methodology to measure donor-specific cell-free DNA after solid-organ transplantation, Clinical Chemistry, 63 (2017) 742–750. DOI: 10.1373/clinchem.2016.264838


Guardingo M., Busqué F., Ruiz-Molina D., Reactions in ultra-small droplets by tip-assisted chemistry, Chemical Communications, 52 (2016) 11617–11626. DOI: 10.1039/C6CC03504C


...genesis of DNA copy number, Analytical Chemistry, 83 (2011) 8604–8610. DOI: 10.1021/ac202028g


Horka M., Sun S., Ruszczak A., Garstecki P., Mayr T., Lifetime of phosphorescence from nanoparticles yields accurate measurement of concentration of oxygen in microdroplets, Allowing one to monitor the metabolism of bacteria, Analytical Chemistry, 88 (2016) 12006–12012. DOI: 10.1021/acs.analchem.6b03758


Jankowski P., Ogónczyk D., Derzisi L., Lisowski W., Garstecki P., Hydrophilic polycarbonate chips for generation of oil-in-water (O/W) and water-in-oil-in-water (W/O/W) emulsions, Microfluidics and Nanofluidics, 14 (2013) 597–604. DOI: 10.1007/s10404-012-1078-4


Jankowski P., Ogónczyk D., Lisowski W., Garstecki P., Polyethyleneimine coating renders polycarbonate resistant to organic solvents, Lab on a Chip, 12 (2012) 2580–2584. DOI: 10.1039/c2lc21297t


Tang M.Y.H., Shum H.C., One-step immunoassay of C-reactive

Sebastian Cabeza V., Kuhn S., Kulkarni A.A., Jensen K.F.,
Authors’ Short Biographies

Adam S. Opalski

MSc Adam S. Opalski obtained his Bachelor’s and Master’s degree in biotechnology from the Faculty of Chemistry Warsaw University of Technology. He is currently pursuing a PhD in the field of microfluidics under the guidance of Prof. Garstecki at the Institute of Physical Chemistry of Polish Academy of Sciences. His research interests lie in investigation of the mechanism of double emulsion formation and use for biological research for which he has recently received a grant from the National Science Centre. Another topic of his studies are high-throughput techniques for droplet generation and manipulation.

Tomasz Kaminski

Tomasz Kaminski is a postdoctoral researcher in the group of Prof. Garstecki at the Institute of Physical Chemistry of the Polish Academy of Sciences in Warsaw. During his PhD studies, he was involved in the development of new micro-droplet technologies to a range of challenges in microbiology and biochemistry. He co-authored 18 publications and 21 patents and patent applications. He has conducted his research projects in collaboration with foreign research groups from Oxford University, University of Wisconsin-Madison, University of Tokyo and 3 spin-off companies: Scope Fluidics, Curiosity Diagnostics and Bacteromic that commercialize microfluidic technologies for medical diagnostics.

Piotr Garstecki

Piotr Garstecki is a full professor at the Institute of Physical Chemistry of the Polish Academy of Science, where he leads the Microfluidics and Complex Fluids Research Group. He obtained his MSc degree in theoretical physics from the College of Science in 1998 and his PhD in chemistry from the Institute of Physical Chemistry PAS. He later served as a postdoctoral fellow in the group of Prof. George Whitesides at Harvard University. He co-authored over a hundred scientific publications and multiple patent applications and co-founded multiple spin-out companies that use microfluidic technologies for the development of medical diagnostic systems.