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Perspectives on atmospheric-pressure plasmas for nanofabrication

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Received 10 November 2010, in final form 6 December 2010
Published 14 April 2011
Online at stacks.iop.org/JPhysD/44/174023

Abstract
Low-pressure, low-temperature plasmas are widely used for materials applications in industries ranging from electronics to medicine. To avoid the high costs associated with vacuum equipment, there has always been a strong motivation to operate plasmas at higher pressures, up to atmospheric. However, high-pressure operation of plasmas often leads to instabilities and gas heating, conditions that are unsuitable for materials applications. The recent development of microscale plasmas (i.e. microplasmas) has helped realize the sustainment of stable, non-thermal plasmas at atmospheric pressure and enable low-cost materials applications. There has also been an unexpected benefit of atmospheric-pressure operation: the potential to fabricate nanoscale materials which is not possible by more conventional, low-pressure plasmas. For example, in a high-pressure environment, nanoparticles can be nucleated in the gas phase from vapour (or solid metal) precursors. Alternatively, non-thermal, atmospheric-pressure plasmas can be coupled with liquids such as water or ethanol to nucleate and modify solution-phase nanoparticles. In this perspective paper, we review some of these recent efforts and provide an outlook for the rapidly emerging field of atmospheric-pressure plasmas for nanofabrication.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Plasma technology plays a vital role in the manufacturing of materials for a wide range of industries [1]. The unique properties of plasma-based processes such as low temperature (close to room temperature) and high-purity are essential to these materials applications. An example of the significant contributions made by plasma processing is the fabrication of integrated circuits (ICs) in the microelectronics industry. The precise etching and deposition that is required in IC manufacturing has been achieved because of the development of advanced plasma tools. A drawback of these processes is that the plasmas are normally operated at low pressure (<1 mTorr) which necessitates expensive vacuum equipment. Shifting the operating regime for plasmas to higher pressures (>1 Torr) could eliminate the heavy infrastructure and maintenance costs associated with low vacuum and significantly lower processing costs. However, at higher operating pressures, plasmas are generally more difficult to sustain and their properties can change dramatically; for example at high pressures, gas temperatures are generally higher which is undesirable for most materials applications. Therefore, one of the important challenges in plasma processing is the development of low-temperature (i.e. cold) atmospheric-pressure plasma sources. The availability of this class of plasmas is expected to open new applications in medicine [2–4], gas treatment [5, 6], textiles [7], surface modification [8, 9] and nanofabrication [10, 11].

Among the various potential applications, nanofabrication is of particular interest. While low-pressure plasmas have been used to etch or deposit materials at length scales now approaching 10 nm [12], there is a limitation to the smallest feature size that can be created. At high pressures, plasmas can be used to prepare materials at length scales below 10 nm by nucleation and growth of materials from atomic or molecular precursors [13]. Although these results
are still in their infancy (especially compared with IC manufacturing), the opportunities offered by atmospheric-pressure plasmas for nanofabrication are rapidly expanding and may soon become an established technology. In addition to the reduction in costs, there are additional advantages offered by atmospheric-pressure plasmas for nanofabrication including non-equilibrium chemistry [14, 15], self-organization phenomena [16, 17], high radical densities [18–21], unprecedented reaction pathways [9, 21, 22] and the possibility of multiphase processing (e.g. plasma–liquid) [23, 24]. In this perspective paper, we discuss recent developments and shed light on the enormous potential of atmospheric plasmas for nanofabrication.

2. Motivation and challenges for atmospheric-pressure plasma processing

2.1. Atmospheric-pressure plasma generation

Operation of plasmas at high pressures (near or at atmospheric pressure) often leads to instabilities (e.g. glow-to-arc transition [25–27]) and elevation of gas temperatures. In general, at high pressures, the increase in frequency of gas-phase collisions results in efficient energy exchange between the ‘hot’ (i.e. electronically excited) species such as electrons or ions and the ‘cold’ neutral atoms (or molecules). This has been observed in one class of atmospheric-pressure plasmas, arcs, where a high voltage is applied between two electrodes and a discharge is ignited and sustained at very high currents (1 A and higher) [6]. Arc discharges have important applications in coatings and waste treatment, but are not suitable for technological applications such as nanofabrication where temperature-sensitive materials may be used. For this reason, much of the modern research in atmospheric-pressure plasmas has focused on generating plasmas with a low gas temperature (so-called non-equilibrium conditions), thus allowing their implementation in a wide range of materials applications. Although we will not comprehensively cover all the configurations and types of atmospheric-pressure plasma sources that have been developed over the years, here we mention a few that are relevant to applications in nanofabrication.

A somewhat straightforward approach to increasing the operating pressure while maintaining the desirable non-equilibrium properties of low-pressure plasmas is to preserve the $pD$ scaling, where $p$ is the pressure and $D$ is the smallest dimension of the plasma [19, 28, 29]. Atmospheric operation is therefore achieved simply by reducing $D$ appropriately (see section 3 for additional details). The generation of ‘microplasmas’ is now well developed and refers to the size of the plasma that is required to achieve stable atmospheric operation, usually less than 1 mm in at least one dimension. The original version of a microplasma, proposed and reported by Karl Schoenbach, was characterized by a microhollow cathode which referred to the small cavity (or hole) on the order of 100 μm in one of the electrodes [30, 31]; since then, a wide range of other configurations have been explored [21].

In general, stable operation at atmospheric pressure is aided by electrode geometry (e.g. microhollow cathode), coupling gas flow (e.g. in plasma jets), cooling the electrodes and selecting a specific gas composition (e.g. with helium) [21, 32]. It should be noted that other types of atmospheric-pressure plasmas, such as corona discharges and dielectric barrier discharges (DBDs), have been studied for many years and rely on some of these approaches. Corona discharges are formed by applying a dc or ac voltage in a pin-to-plane electrode geometry where the pin is usually on the order of a millimetre or less in diameter. The inhomogeneous electric field generated near the pin electrode leads to breakdown and stable sustainment of a discharge at high pressures. DBDs, also referred to as barrier or silent discharges, are characterized by at least one dielectric electrode, a gas gap and a counter electrode. Applying an ac electric field results in the formation of hundreds of short-lived and localized current filaments (or micro-discharges) that fill the volume between the electrodes [33]. Coronas and DBDs rely on a self-limited supply of charges to prevent excessive heating and instabilities; alternatively, pulsed excitation can help stabilize atmospheric-pressure plasmas and avoid glow-arc transitions. Recently, Pai studied nanosecond repetitive pulsed and found that the short pulse duration could prevent spark formation in air discharges at atmospheric pressure [34, 35]. Thus, a number of approaches are now available to stabilize plasmas at atmospheric pressure and enable chemical and materials applications.

2.2. Nanofabrication in the gas, solid, or liquid phase

Among the different types of atmospheric-pressure plasmas, microplasmas have elicited the most interest for nanofabrication. While the reasons are not obvious, we surmise that microplasmas are easier to operate than DBDs, because of their small scale and low power requirements and, unlike coronas, gas flow can be coupled directly to the discharge (with a tube electrode) facilitating materials synthesis and processing. Furthermore, microplasmas can be generated with virtually no restrictions on the gas composition and, therefore, allow for a broad selection of precursors. For this reason, our discussion on nanofabrication will focus primarily on microplasmas; we acknowledge that other atmospheric sources may also find applications in the near future.

As mentioned earlier, at high pressures, collisions in the gas phase are enhanced—this property of atmospheric-pressure plasmas is especially attractive for gas-phase nanoparticle synthesis. At low pressures, plasmas are used to dissociate molecular precursors and form reactive radicals which can interact with a substrate to etch or deposit a thin film. At high pressures, gas-phase collisions between the radical moieties lead to homogeneous nucleation of small particles. In a large-scale plasma, the particles continue to grow, agglomerate and deposit on the electrodes and walls of the reactor [36]. The advantage of a microplasma is that particle growth and agglomeration are limited, thus allowing the synthesis of nanometre-sized particles with narrow size distributions (see figure 1) [37].

Atmospheric-pressure microplasmas can also be formed with surfaces (i.e. films of nanomaterials) to promote self-organization of nanostructures. Previous experiments
have shown that the generation of localized electric fields at the surfaces of nanoscale features (by a plasma) can provide energetically favourable paths for adatom diffusion [16, 17, 38]. Although this mechanism is also present in low-pressure plasmas, at atmospheric-pressure, the selective nanoscale reactions are significantly enhanced.

Non-thermal, atmospheric-pressure operation makes it possible to couple microplasmas with liquid electrodes as well. When a microplasma is formed at the surface of a liquid, the ions, electrons and other excited species in the gas phase interact with and initiate reactions in the solution. This chemical approach is potentially useful to nucleate and grow colloidal nanoparticles or modify the surface chemistry of nanoparticles. Similarly, microplasmas have been generated inside a liquid; this has resulted in the formation of a nanoscale plasma that may find new applications in biological and materials applications (for example direct patterning of nanostructures). In the next section, we discuss these examples of atmospheric-pressure plasmas for nanofabrication.

3. Modelling and experimental studies of atmospheric-pressure plasmas for nanofabrication

A key difference between low-pressure and high-pressure plasmas is that at high pressures, collisions between the ‘hot’ electrons and/or ions and the ‘cold’ neutrals result in efficient energy exchange which can lead to thermal effects that limit the usefulness of atmospheric-pressure plasmas for nanofabrication. Thermally equilibrated plasmas such as arcs where the gas temperature is well above room temperature (>1000 K) cannot be used in applications that require temperature-sensitive materials. In addition, thermal plasmas are characterized by relatively low electron energies (<0.1 eV mean electron temperature) which limit their ability to dissociate chemical precursors and prevent material synthesis via kinetic pathways. To address these issues, we briefly describe here the thermal properties of atmospheric-pressure plasmas, from a modelling perspective, which must be controlled to enable applications in nanofabrication.

The effect of electron heating (i.e. transfer of energy from electrons to neutrals) at high pressures can be captured by a zero-dimensional (0D) model where the energy gained by the plasma as thermal energy is compared with energy losses through the surface of the confined plasma volume [21]. In this 0D model, the thermal energy and the surface losses are expressed by the following equations:

\[
\frac{P_{\text{heat}}}{V} = \varepsilon(T_e)n_eK_e(T_e)
\]

\[
\frac{P_{\text{cool}}}{V} \propto n_eT_g^{3/2} \frac{p}{D^2},
\]

where \(P_{\text{heat}}\) refers to the energy transferred as thermal energy (in terms of a power density), \(P_{\text{cool}}\) refers to the energy lost to the surface (in terms of a power density), \(V\) is the plasma volume, \(\varepsilon\) is the average energy exchanged per collision, \(n_e\) is the gas density, \(n_e\) is the electron density, \(K_e\) is the collision rate, \(T_e\) is an effective electron temperature, \(T_g\) is the gas temperature, \(p\) is the pressure and \(D\) is a linear parameter that refers to the size of the plasma. In figure 2, we have evaluated and plotted \(P_{\text{heat}}\) and \(P_{\text{cool}}\) as a function of the electron temperature and gas temperature. To calculate the collision rate in equation (1), we used typical cross sections characterized by a functional form that included an energy threshold, an increase with increasing energy and, at very high energies, a slow decay to very low values. The qualitative behaviour described in figure 2 is confirmed by common experimental observations (e.g. [39]).

Figures 2(a) and (b) compare the thermal behaviour of a ‘bulk’ plasma, where \(D = 1.0\) cm, to that of microplasmas, where \(D\) is reduced to 0.1 cm and 0.03 cm, respectively. Assuming that the plasmas are energetically balanced, the power density input should be equal to the power density lost. This value, which represents the thermal power density exchanged, determines the two temperatures that coexist in the plasma, i.e. \(T_g\) and \(T_e\) (indicated by the red points). As shown in figure 2(a), at low power densities, \(T_g\) is much lower than \(T_e\); as the power density increases, the two temperatures approach one another until \(T_g = T_e\) (i.e. thermal equilibrium). It is important to note that the size of a plasma, defined as \(D\) in equation (2), has the effect of shifting up/down the power density lost (blue curve); for example in figure 2(b) the power density lost shifts up as \(D\) is decreased (see \(D = 0.1\) cm). Thus, reducing the size of a plasma helps preserve non-equilibrium conditions even at high pressures (up to atmospheric) and high-power densities. This property represents the key motivation for using microplasmas in high-pressure applications of plasmas [21].

Figure 1. TEM images of Ni\(_x\)Fe\(_{1-x}\) nanoparticles synthesized from various combinations of the respective metalloocene vapours for Ni and Fe in a continuous-flow, atmospheric-pressure microplasma: (a) Ni NPs (3.2 nm mean diameter); (b) Ni\(_{52}\)Fe\(_{48}\) NPs (3.2 mean diameter); (c) Ni NPs (2.0 nm mean diameter); (d) Ni\(_{52}\)Fe\(_{48}\) NPs (2.0 nm mean diameter). Insets show HRTEM images of nanoparticles from corresponding low magnification TEM images with lattice spacings indicated.
Results for the 0D model of energy flow in atmospheric-pressure plasmas. The energy input as thermal energy (pink curves) and the energy output as losses at the surface of the plasma (blue curves) are calculated as a function of the input power density and the characteristic electron ($T_e$) and neutral gas temperatures ($T_g$) in the plasma. The transition from a non-equilibrium ($T_e < T_g$) to a thermally equilibrated ($T_e = T_g$) regime as the input power density changes is shown for (a) a ‘bulk’ plasma where the dimension, $D$, is 1.0 cm and (b) microplasmas where the dimension, $D$, is decreased to 0.1 and 0.03 cm.

An atmospheric-pressure microplasma set-up used for the gas-phase synthesis of nanoparticles from gas or vaporized precursors.

**Figure 3.** An atmospheric-pressure microplasma set-up used for the gas-phase synthesis of nanoparticles from gas or vaporized precursors.

### 3.1. Gas-phase synthesis

Gas-phase nucleation of nanomaterials in a microplasma from vapour precursors (e.g. figure 3) is a natural extension of previous studies with low-pressure plasmas [10] and larger-scale atmospheric plasmas and jets [40, 41]. There are many different precursors that are available, generally referred to as chemical vapour deposition (CVD) or metal-organic chemical vapour deposition (MOCVD) precursors, that can be non-thermally dissociated in a microplasma to grow different types of materials (i.e. metals, semiconductors and oxides). The general mechanism for nucleation is to introduce the precursor in the microplasma and form reactive radical species. These radicals can collide, react and nucleate small clusters at the appropriate process conditions. The clusters will then grow, by additional radical or vapour deposition on the particle surface, or agglomerate, through collisions with other particles. Finally, the particles will exit the plasma volume as an aerosol flow. This approach has been successfully used to synthesize carbon nanomaterials [42–45], silicon nanoparticles [37–47] and metal nanoparticles [48, 49]. Compared with low-pressure plasma experiments (e.g. [50]), the particles synthesized by these routes are much smaller because of the shorter residence time experienced by the growing particles in the reactor [37]. Overall, these studies reflect the promise of microplasma-based synthesis routes for continuous and tuneable preparation of high-purity nanometre-sized (i.e. 1–5 nm) particles at atmospheric pressure.

A distinct advantage of nucleating nanoparticles in a microplasma from a vapour source is the ability to synthesize bimetallic or alloyed nanoparticles. For example, vapours of different metalocene compounds have been combined in controlled ratios to obtain Ni$_x$Fe$_{1-x}$ nanoparticles of varying size and composition (where $x$ = Ni atom fraction) [51]. The chemical composition of Ni and Fe in the as-grown particles was verified by energy-dispersive spectroscopy (EDX) and found to be within 10% of the relative ratio of nickelocene and ferrocene used in the microplasma. The formation of compositionally tuned bimetallic nanoparticles could have important implications in catalytic applications such as the growth of chirally enriched single-walled carbon nanotubes (SWCNTs) [52].

Direct evaporation, sputtering or etching of solid materials is an alternative approach that has been explored via atmospheric-pressure microplasma synthesis [16, 53–64]. A critical challenge for this method is how to control the
mechanism for particle nucleation and growth which depends on many factors including the evaporation rate of the solid metal source. The mechanisms responsible for the surface reactions at the solid precursors are still not clear as there is no comparable process. Nonetheless, there are significant advantages to using solid metals in terms of minimizing the amount of precursor and handling of dangerous gases or other chemicals [65].

Despite difficulties in generating stable, large-scale atmospheric-pressure plasma systems, there have been a few reports of nanomaterial synthesis in these systems as well. Carbon nanotubes (CNTs) have been synthesized in a parallel-plate reactor operated at atmospheric pressure [66]. Iron and carbon nanoparticles have been also produced at near-ambient temperatures with an atmospheric-pressure plasma in a shower-head configuration [67]. In the latter case, the diameters of the as-grown particles were in the range 20–35 nm which clearly shows the effect of residence time when compared with the sub-10 nm particles produced by atmospheric-pressure microplasmas. It is expected that in the coming years, hybrid configurations will be developed where the favourable features of microplasmas are combined with larger-scale reactors to produce scalable quantities of well-defined nanomaterials.

3.2. Plasma–liquid chemistry

There have been reports of plasmas formed inside or on the surface of liquids dating back as far as 100 years ago [24,68,69]. Recently, there has been renewed interest in the generation of plasmas with liquids because of potential applications in medicine [70] and materials synthesis [68,69,71–77]. For example, interfacing plasmas with liquids could enable the synthesis and/or functionalization of nanostructures in the solution phase [23]. The preparation of colloidal dispersions of nanomaterials offers important benefits for applications of these materials in analytical chemistry and medicine [78–80].

While low-pressure plasmas have been used to produce nanomaterials in a liquid phase, these applications are generally limited to liquids with low vapour pressures such as molten salts (i.e. ionic liquids) [68,73]. Recent advances in the generation of non-thermal, atmospheric-pressure plasmas have greatly facilitated the coupling of plasmas with more common liquids such as water and ethanol, which opens up a wide range of potential applications [68,69,73–77]. Plasmas have been used to synthesize metal nanoparticles in aqueous solutions and modify the surface of silicon nanoparticles [68,69,73–77]. Overall, there is general agreement that reactions at the gas–liquid interface induced by a plasma lead to unique processing conditions; however, the underlying mechanism remains poorly understood. Some studies have speculated that gas-phase electrons from the plasma initiate electrochemical reactions in the solution such as reduction of metal cations or oxidation of the anode electrode [73,68]. Others have proposed that the plasma causes dissociation of water to produce hydrogen radicals that react and reduce aqueous metal cations [75]. In each of these cases, it is clear that the plasma is essential; for example, it would not be possible to synthesize Au nanoparticles with standard reducing agents in an alkaline solution and in an electrochemical cell the metal cations would plate on an electrode rather than nucleate nanoparticles [69,75]. Other advantages of plasma–liquid chemistry are the fast kinetics [68], high-purity [68], ability to control dispersion [75,76], potential to control the shape (i.e. faceting) [69] and the absence of toxic reducing agents [69,73].

An interesting direction for plasma–liquid chemistry is the possibility of functionalizing nanostructures by electron-induced molecular dissociation (or ion-induced) [69]. Gas-phase electrons generated in a plasma are normally used to dissociate or interact with gas molecules to drive chemical reactions. Electron impact dissociation (EID) has been one of the hallmarks of plasma processing whereby reaction kinetics can be de-coupled from the overall system thermodynamics. In a plasma–liquid system, these same electrons (or ions) may be able to break bonds of molecular species in a liquid and initiate liquid-based reactions through the formation of various radicals, ions and excited species. Therefore, the same principle utilized in gas-phase plasma chemistry may be extended to the plasma–liquid interface. Furthermore, control of the electron energy distribution should be easier at the plasma–liquid interface where sheath effects are important. These reactions are unique to a plasma–liquid environment since the energies of electrons are much higher than those available in wet chemistry where heating is the main source of energy [69].

An example of plasma-induced chemistry in solutions is dissociative electron attachment (DEA). This reaction mechanism would, for example, make it possible to dissociate a functional group from a molecule without complete dissociation into atomic moieties. DEA is of great interest because the dissociation of specific functional groups is highly dependent on the energy of the incoming electron and therefore different functional groups can be selectively dissociated. The first step in DEA is electron-induced excitation of a neutral molecule from the ground state AB to a resonant state AB*− (figure 4).
Since electron auto-detachment would form an unstable molecule, dissociation of the excited complex results in the formation of $A + B^-$. This mechanism has been previously reported for electron beam excitation of various solutions from alcohols to water [81–84]. As illustrated in figure 4, excitation and attachment are activated by a very narrow distribution of electron energies which suggests that electrons from a non-equilibrium plasma could be used to initiate DEA selectively.

There is now experimental evidence that a microplasma can be used to functionalize silicon nanocrystals (Si NCs) by this approach [77]. In that study, hydrogen- and oxygen-terminated Si NCs synthesized by electrochemical etching were dispersed in ethanol and exposed to a microplasma at the surface of the solution. We speculate that DEA results in excitation of the ethanol molecules and subsequent reaction with the surface of the Si NCs. After functionalization, the surface chemistry was analysed by Fourier transform infrared (FTIR) spectroscopy which confirmed that the hydrogen and oxygen groups on the surface of as-grown Si NCs were replaced by organic and OH groups. After functionalization, the Si NCs exhibited much stronger photoluminescence emission with a red-shift of the peak energy by approximately 80 nm. Further investigation of the plasma parameters and liquid chemistry should allow more careful control over the chemical and optoelectronic properties of Si NCs via tailored surface functionalization.

3.3. From micro- to nanoscale plasmas

As previously described, confining a plasma to smaller dimensions allows non-equilibrium conditions to be maintained at higher pressures and higher power densities (see figure 2). This has led to questions, perhaps born out of scientific curiosity, along the lines of how small can we confine a plasma and, at these new dimensions, how would the properties of the plasma change? Using the 0D model, we can deduce that as the volume of a plasma is reduced, the line representing \( \frac{P_{\text{cool}}}{V} \) will eventually reach a position (see figure 2(b), \( D = 0.03 \text{ cm} \)) that cannot intersect with the curve representing \( \frac{P_{\text{heat}}}{V} \). In physical terms, this could signify that at some critical dimension, the electron-induced gas heating becomes self-limited whereby increasing the electron temperature does not cause any further increase in gas temperature. We speculate that at these conditions a new regime for plasmas exists, which may lead to unprecedented synthesis capabilities. We note that other factors could prevent formation of a plasma under these conditions. For instance, a ‘non-Debye microplasma’, where Debye shielding may be compromised, could influence the plasma state [21]. In either case, this regime would be characterized by a very high power density (>1 GW cm\(^{-3}\)) and chemical reactivity, at low gas temperature, making these plasmas fundamentally different from other high-power density plasmas such as sparks or pulsed plasmas. Furthermore, the absence of transients in the reaction kinetics, which are present in pulsed discharges, could allow highly controlled and uniform synthesis of nanomaterials. However, there are technological challenges for the generation of such plasmas including electrodes, heat conduction, power coupling, etc, which may restrict the range of suitable conditions for the ‘heat-limited regime’. Nonetheless, recent work with supercritical fluids suggests that plasmas can be formed at these unique processing conditions; critical fluids exhibit a very high heat capacity that helps shift the power loss line, producing a heat-limited regime at larger plasma volumes. Indeed, interesting nanomaterials have been synthesized by these cryogenic plasmas such as nano-diamonds [85], illustrating the potential advantages of this environment for nanofabrication [86–88].

Alternatively, in any liquid, the pressure (i.e. density) of a fluid is increased and plasmas are naturally confined to smaller dimensions. Plasma generation in liquids has attracted researchers from many different fields [24] and recently has been explored for nanomaterial synthesis. Examples include laser-produced plasmas [89] and DBD-type plasma processing [90]. However, the generation and characterization of glow-like discharges in liquid is still a clear challenge. To address these issues, researchers have coupled nanosecond pulsed power; this has allowed the remote generation of nanoplasmawith floating CNT electrodes (figure 5) [78, 91]. In this case, the nanoplasma was used as an optical source to analyse the liquid solution that the CNTs were immersed in. However, very similar processes may be envisioned for nanomaterial synthesis whereby remotely activated plasmas are used to functionalize and/or synthesize composite nanomaterials (e.g. core–shell particles). Liquid applications of plasmas would open up new technological areas ranging from low-cost printable photovoltaics [92, 93] to drug delivery [94, 95] to bio-imaging [79] to sensing [78, 91]. Therefore, it should be readily apparent that interfacing atmospheric-pressure plasmas
with liquids is an exciting new direction for plasma science and technology.

4. Conclusions and outlook

In this perspective paper, we have highlighted some of the challenges, progress and exciting potential of atmospheric-pressure plasmas for nanofabrication. While atmospheric-pressure operation of plasmas has in the past faced challenges because of instabilities and gas heating, recent developments in plasma sources (e.g. microplasmas) have allowed significant progress. Atmospheric-pressure plasmas offer key advantages, as compared with low-pressure plasmas, for the synthesis of a wide range of nanomaterials including aerosol nanoparticles, nanostructured thin films, CNTs and colloidal nanoparticles, to mention a few. In addition, atmospheric-pressure plasmas are characterized by a unique environment that may open new applications for plasmas such as plasma–liquid chemistry.

Despite the potential that atmospheric-pressure plasmas hold for nanomaterials synthesis, some challenges remain. There are problems associated with plasma heating and stability at atmospheric pressure that have prevented application in industrial processes. Atmospheric-pressure plasmas are fundamentally different from low-pressure plasmas because gas-phase collisions dominate over plasma–surface interactions. The reaction/collision kinetics has consequences on the collective behaviour which still needs to be fully understood. Nonetheless, significant strides have been made in recent years and the potential of atmospheric-pressure plasmas for nanofabrication is clear and exciting.

Acknowledgments

RMS thanks the NSF Career Award Program (CBET-0746821), Camille Dreyfus Teacher-Scholar Awards Program, and AFOSR Young Investigator Award Program for funding support. DM wishes to thank Joanne McKenna and Randolph Walter (University of Ulster, UK) for useful discussions and support.

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