Microfluidic Stretchable Radio-Frequency Devices

This paper describes a new packaging technology based on microfluidics to realize physically deformable radio-frequency circuitry, admitting new possibilities in merging structure and function in high-performance electronic systems.

By Zhigang Wu, Klas Hjort, and Seung Hee Jeong

ABSTRACT | Recently, the shrinking of the personal computer market has given a clear signal that it is time to divert our focus from the strategy of miniaturization of transistors to a different strategy with emerging technologies. As a new form of electronics, stretchable electronics has significantly advanced in the past few years by micro/nanofabrication of thin films of traditional stiff and hard materials such as silicon, metals, and ceramics, and especially subsequent transfer process on an elastic substrate. However, such a thin structure often suffers from high resistance that leads to low performance when long structures are required. This is particularly true for antennas in radio-frequency (RF) electronics. By introducing microfluidics into RF electronics, we found out that it was an excellent way to make high-performance stretchable RF electronics. Apart from antennas, the microfluidic approach was also adopted and further developed to various devices with integrated wireless communication. This fusion of microfluidics with RF electronics brings not only a lot of opportunities for researchers as a radically new research field, but also potentially commercial benefits for industry. As a new emerging field, a huge effort, ranging from fundamental science to technology development, is required to realize it. This paper illustrates the fundamentals in processing and relevant applications, and highlights recent advances in microfluidic RF electronics. The authors would like to inspire the electronics community to further exploit the advantages of this approach and accelerate innovations in this field.

KEYWORDS | Elastic substrate; microfluidic electronics; radio-frequency (RF) device; reconfigurable system; stretchable electronics

I. INTRODUCTION

Excellent user experience and hence improved acceptance strongly influence today's innovations, which often result in new product design or novel technology development. Of particular significance in the electronics industry [especially in the integrated circuits (IC) and packaging industry], the improvement of the technology has been mainly driven by continuously reducing basic component's size and hence enhancing computing performance during the last decades, which is often summarized and referred to as Moore's law [1]. This continuous computing speed enhancement has revolutionized our societies, and totally changed our lifestyle by bringing us enhanced productivity in offices and factories. The development of the central processing unit (CPU) in the personal computer (PC) has followed Moore's law nearly perfectly. However, the present shrinkage of the PC market is giving us a clear warning signal [2]: Its focus on higher density in smaller components is not going well as has happened in the past decades [3]. Innovations in new platforms or even a radical technical revolution are necessary to meet the new demands from society.

Differing from the traditional silicon-based electronics, other technologies such as "beyond Moore" [3] or "more than Moore" [4] are emerging, for example, carbon electronics which is based on carbon nanotubes and graphene, organic electronics, printed electronics, and biological computation. As one of the "more than Moore" technologies, flexible electronics has been recently

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emphasized again [5]. Assembling electronic devices via hybrid integration on flexible substrates, especially in plastic foils, flexible electronics has pioneered high flexibility and bendability. It has been invaluable in reducing weight and volume of electronics in aerospace applications. Since the 1980s, it has been highly accepted in handheld devices and wearable, medical, and consumer products. In the recent past, novel technologies such as heterogeneous devices have been integrated with printed electronics, providing lighter weight and thinner system, or cost reduction. However, when used in many other applications that target sensitive and soft surfaces such as the human body, its limited mechanical compliance often renders it inadequate [6].

In contrast to the traditional rigid and brittle silicon-based electronics, elastic substrate- or carrier-based stretchable electronics [6]–[9] was developed thanks to its high mechanical compliance when it is attached to complex and soft surfaces such as our skin, eyes, or inner organs. This is of particular interest in regards to many devices which require ergonomic interfaces to enhance their user experience, e.g., contact lenses which intimately interact with an eye. Employing a soft format, stretchable electronics not only relies on a static deformable system, but may also be employed in dynamical systems. Many highly attractive features have been demonstrated [10], [11]. For example, Rogers' group at the University of Illinois at Urbana-Champaign introduced the so-called epidermal electronic system [12]. Being mechanically adjusted to the human skin, the devices could be conformally laminated onto the body like a temporary tattoo, measuring various physiological signals, e.g., in electroencephalograms, electrocardiograms, and electromyograms, and potentially forwarding the data wirelessly. With much better contact with the objects to be probed (human skin or organs), elastic electronics could provide data of higher accuracy than that provided by traditional devices. Ultimately, this kind of new technology may have a chance to reshape the concept and format of electronics, and potentially revolutionize our daily life as user-friendly man-machine-multi-interfaced smart phones and tablets have done in the past decade.

As discussed above, one of the most important features of elastic electronics is excellent mechanical stretchability. To comply with this feature, the essential parts of electronics, substrate, and conductors should be stretchable. Unfortunately, traditional carriers (such as silicon, or rigid and flexible printed circuit boards) have a very limited stretchability and are not suitable for new applications which demand compliance and dynamic conformability. Hence, a new kind of substrate material should be sought for when thinking about the new requirements of conformal electronic systems.

One of several potential materials systems is elastomers such as natural or synthetic rubbers. One of the synthetic rubbers, polydimethylsiloxane (PDMS), is the most commonly used elastomer in the microfluidic and related micro/nanocommunities. Initially, PDMS was developed in the United States during World War II. At the end of the last century, together with the so-called soft lithography, PDMS was introduced into the microfluidic community [13], [14]. It demonstrated great advantages in microfluidic device prototyping by rapid processing, ease of fabrication, cost-effectiveness; and by being chemically inert, nontoxic, gas permeable, and optically transparent [15]. These properties allowed researchers to explore many interesting biological applications, which opened up new possibilities in biological and medical science [16].

As a polymer, PDMS has a formula of $CH_3[Si(CH_3)_2O]_nSi(CH_3)_3$, where n is the number of repeating backbone units. Its backbone $[SiO(CH_3)_2]$ is quite flexible due to the siloxane linkages, which could be analogous to the ether linkages used to impart rubberiness in polyurethanes [17]. Such kind of flexibility at the molecular level provides PDMS with excellent mechanical properties, which are desired for soft electronics: compliance, bendability, twistability, and stretchability, as well as good electric insulation. Some of its mechanical features are summarized in Table 1, comparing it to common

Table 1 Comparison of Mechanical Properties of Rigid and Soft Substrate Materials

	Si	Polyimide (Kapton)	PDMS	TPU (average)
Young's modulus [GPa]	112.4	-	$3.6\text{-}8.7\times10^{-4}$	0.0196
Yield strength [MPa]	120	69	-	16.1
Ultimate tensile strength [MPa]	120	231	1.55 – 9.0	34.9
Poisson's ratio	0.28	0.34	0.5	-
Elongation at breakage [%]	-	72	up to 1,000	584
Electrical resistivity [Ω·cm]	0.01	1.5×10^{17}	$2.4\text{-}15\times10^{14}$	3.01×10^{11}
Dielectric constant	11.8	3.4	2.77 – 3.69	6.34

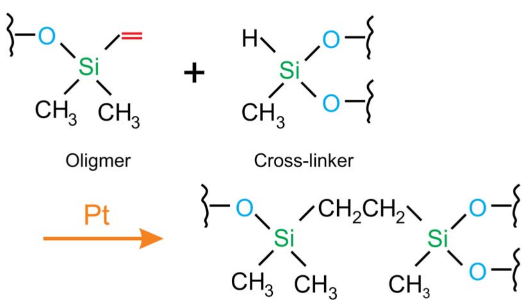

Fig. 1. ***Chemical reaction or polymerization scheme of the two components of PDMS used in laboratory.***

substrates such as silicon, polyimide, and another common elastomer, thermoplastic polyurethane (TPU). PDMS elastomer may be obtained either by condensation or by addition reactions. In the laboratory environment, two-component-based addition reaction is often used, as shown in Fig. 1, due to its convenient processing and no demands for costly instruments. In summary, microfabricated PDMS has a favorable mechanical performance, and withstands severe twisting and stretching without mechanical failure. All of this makes it attractive for use in stretchable electronics.

To create a stretchable circuit, it is necessary to include conductors with the PDMS substrate without obstructing its excellent mechanical flexibility. One straightforward way is to deposit a thin layer of solid metal, such as gold, on the PDMS substrate, using various thin film deposition techniques [18]. However, the intrinsic mechanical and chemical mismatch between the directly deposited thin solid metal and the elastic substrate sets a very low limit for the mechanical stretchability. Hence, it has low electrical reliability when stretched. Later, investigations showed that pre-stretching of the substrate prior to thin metal deposition greatly improved its mechanical stretchability [19], [20]. The stretched metal layer often demonstrated a wavy cross section. As a result of this phenomenon, micro/nanofabricated thin inorganic layers (silicon, gold on polymer, and so on) mimicked this wavy structure on or inside PDMS to achieve very high degrees of mechanical deformability [21]. Such shape of thin foils could be designed to achieve wrinkles either in out-of-plane [22] or in-the-plane forms [12]. Together with transferring printing technology, this approach formed elastic electronics and has demonstrated potential in many interesting applications, e.g., a high-performance artificial eye sensor [11], surface-mounted ergonomic biomedical sensors [10], and epidermal electronics systems [12]. However, the demand for highly dedicated and advanced equipment for the processing hinders rapid diffusion of the technology and sets a high cost per area of the device. In addition, a conductor of elastic electronics that is made of a thin film will not allow low resistance with a long feature,[1] which is a strong demand in high-quality RF circuitry and antennas for modern wireless communication to ensure excellent user experience and user acceptance. With a conductor made of a solid metal thin film, the good user experience from this new technology would be diminished in stretchable wireless systems. Therefore, a new solution is necessary to meet these requirements.

In principle, liquids in elastic microchannels can reach an extreme level of deformation without any hysteresis since they can freely flow in the channels without any discontinuity. Microfluidic technology is proposed for building a conformal electronic system by embedding liquid conductors and electronic devices and circuits into elastomer materials such as PDMS [23]. This should be an excellent combination for obtaining a high degree of stretchabiliy if we could find a proper conductive fluid. Looking back to the beginning of the past computing era, tiny liquid mercury (Hg) drops were used in punch-card readers to read input information. The major concern for this approach was the use of mercury, due to its high toxicity on humans and our environment. With a low melting temperature and very low toxicity, the gallium-based alloy Galinstan was developed in the last century as a replacement for Hg. With its high electrical conductivity, it opened up a door to make low-resistance RF components for high-quality wireless communication for stretchable systems by combining microfluidics with RF electronics.

II. MICROFLUIDIC STRETCHABLE ELECTRONICS

A. Highly Conductive Liquids

In traditional microfluidics, electrolyte solutions have been the most common liquid conductors that we have dealt with. However, due to their low electrical conductivity they are far from being sufficient electrical conductors in RF electronic components, as mentioned earlier. As a conductive liquid metal, mercury has been well known for thousands of years and was widely used in many applications such as in thermometers, barometers, and fluorescent lamps. In microfluidic applications, mercury has been used in the form of drops as miniaturized versions of the macroscale thermal and electric contacts [24], [25]. However, because of its high toxicity, it is not allowed to be used in many countries. Due

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[1] Due to the skin effect, the charges tend to flow on the surface in an RF system. Hence, at high enough frequencies the thin film approach might reach similar resistance as those based on thick film. However, as we will discuss in the following section, due to practical reasons most of stretchable systems work in the ultrahigh-frequency range (UHF, 300 MHz–3 GHz), where a film of several micrometers is required for a high-quality low-resistance system. Unfortunately, to maximize the stretchablity of the thin-film-based system, a thin film of solid metal should be made as thin as 100-nm scale, which is far from reaching low enough resistance for a high-quality UHF RF system.

to its very low vapor pressure in air, it can be easily inhaled and block many important physiological functions, severely damaging the body. It can also form potent toxins, such as dimethylmercury and methylmercury in organic compounds. Fish and shellfish have a natural tendency to concentrate these compounds in their bodies and, by biomagnification, severe mercury poisoning may occur in species that are higher on the food chain, such as humans.

In order to find a suitable replacement, the focus was shifted to low melting temperature alloys, such as the NaK alloy, Wood's metal, and Field's metal. As room temperature liquid alloys, the gallium-based alloys stand out due to their many excellent features. First, they are neither toxic (like Hg) nor reactive (like NaK). Second, they are liquids in quite a broad temperature range. For example, Galinstan (a eutectic alloy of gallium, indium, and tin, with smaller amounts of other elements) is liquid from −19 °C to above 1300 °C [26], [27]. From the perspective of stretchable RF electronics, bulk Galinstan has comparatively high electrical conductance, about 6% of that of bulk copper (Table 2). Note that Table 2 presents the direct current (dc) conductivity. Due to the skin effect, at a high enough frequency, the RF resistance depends much on the geometrical design of the conductor besides its bulk dc resistance. According to the antenna theory, the size of an efficient antenna is inversely proportional to its working frequency. In practice, very small antennas that are working in the extremely high-frequency band (EHF, 30–300 GHz) do not require as high stretchabilty as in the ultrahigh-frequency band (UHF, 300 MHz–3 GHz) do to being able to conform to a targeted surface. Therefore, stretchable microfluidic RF electronics have been demonstrated at the UHF band or below. At 3 GHz, the skin depth is 1.19 and 4.94 μm for copper and Galinstan, respectively. Following its basic equation, the skin depth is ten times smaller for a hundred times higher frequency or a hundred times higher conductivity (the magnetic permeability of nonmagnetic metals such as copper and Galistan is approximately one). Hence, the skin effect will not be emphasized from here on. Another kind of liquid or liquid-similar conductor is a gel-like substance (or paste), which, in most cases, is a composite [28]. This kind of substance can normally be deformed to some extent. However, it usually suffers from low electrical conductivity, which is not enough for high-quality RF electronics. Therefore, we will not discuss it further in this paper.

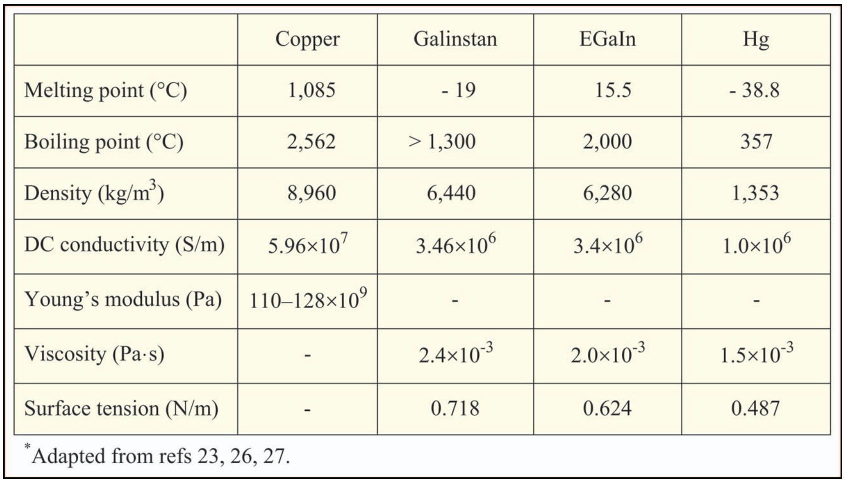
B. Transferring Microfluidic Technology Into Electronics

Because liquids and elastomeric materials have dramatically different mechanical characteristics compared to traditional rigid electronic materials, the fabrication techniques for liquid-alloy-based stretchable electronics have been developed and demonstrated to maintain these features. How to introduce the desired fluidic circuits into an elastic carrier is the core of the whole fabrication. According to the way of handling the liquid alloy, the method can be roughly categorized into two types: liquid filling or injection (into a channel) and liquid printing. The former is a serial process while the latter could be a parallel process.

Liquid alloy filling or injecting into the fabricated elastic channel by soft lithography was the first demonstrated technique to make high-performance antennas stretchable [29], [30] (Fig. 2). Typically, the fabrication process flow follows that of PDMS prototyping of microfluidics and is as follows.

1) As a structure layer, SU-8 (a negative photoresist) is spun on a precleaned silicon wafer.
2) The channel network design is converted to a mask pattern and then transferred onto the SU-8 using a selective ultraviolet (UV) exposure. The developed and solidified SU-8 structure on silicon then serves as a master for the following step.
3) The channel network is replicated into PDMS by pouring and curing the well-mixed PDMS mixture

Table 2 Comparison of Physical Properties of Copper, Galinstan, EGaIn, and Mercury



	Copper	Galinstan	EGaIn	Hg
Melting point (°C)	1,085	- 19	15.5	- 38.8
Boiling point (°C)	2,562	> 1,300	2,000	357
Density (kg/m^3)	8,960	6,440	6,280	1,353
DC conductivity (S/m)	5.96×10^7	3.46×10^6	3.4×10^6	1.0×10^6
Young's modulus (Pa)	$110–128\times10^9$	-	-	-
Viscosity (Pa·s)	-	2.4×10^{-3}	2.0×10^{-3}	1.5×10^{-3}
Surface tension (N/m)	-	0.718	0.624	0.487

*Adapted from refs 23, 26, 27.

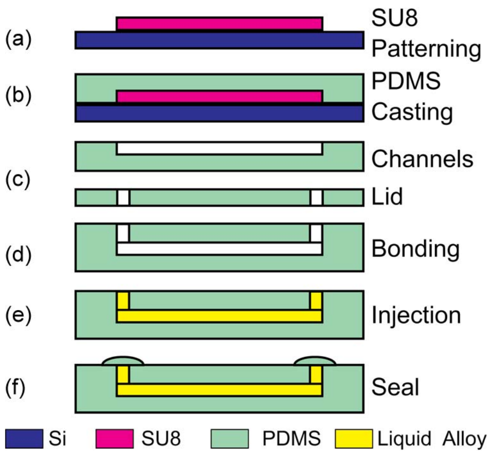


Fig. 2. ***General process of filling of liquid alloys.***

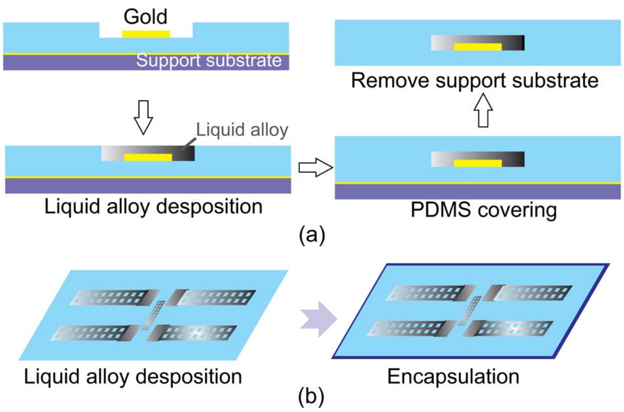


Fig. 3. ***Printing process with an intermediate layer (a) and a general concept to make liquid alloy circuit by printing (b).***

with monomer and cross linker on the surface of the SU-8 master. In parallel, another blank PDMS slab with a similar size is prepared by pouring and curing the mixture on a blank silicon wafer. To allow for smooth liquid filling, the holes for letting in the liquids should be punched before the two PDMS layers are bonded together.

4) With high-energy exposure (such as oxygen plasma, UV, ozone treatment), the two pre-cleaned PDMS layers are bonded together to form a closed channel.
5) The channel network is filled with a liquid alloy either by injecting with a pressurized liquid alloy flow or sucking with a vacuum.
6) Finally, the fabrication is finished by inlet/outlet sealing. In principle, by stacking a few layers of channels, this fabrication technique could be further extended for multilayer processing.

Considering the huge surface energy difference between the liquid alloy and the PDMS substrate, a mixed process of thin film deposition and printing was developed by sputtering an intermediate wetting layer [Fig. 3(a)]. In the practical operation, prior to liquid alloy printing with a Teflon squeegee, a thin layer of gold was sputtered onto the PDMS channel to promote wetting between the liquid alloy and the channel walls [31]. This ensured high wetting between the channel and the liquid alloy but at the cost of increasing the complexity of the whole fabrication process significantly. Recently, freezing casting of the liquid alloy has been shown to make soft electronics [32]. In addition, besides bulk liquid alloy filling, a porous distribution of liquid alloy by filling a 3-D fabricated PDMS matrix could enhance the stretchability significantly [33].

However, the capillary filling process sets severe limits on this technique. In this process, it is preferable that the channels connect together at a rather short length for a simple pattern. When isolated conductive parts or a larger number of very long channels are needed in the design, multiple liquid alloy injections are required, which will dramatically reduce the reliability of the process. Furthermore, the filling process is difficult to scale up for batch type production. The resulting low reliability and yield of injection of liquid alloys would become a big obstacle when considering actual production. Hence, parallel based or automated processes, such as printing in Fig. 3(b), are desirable for versatile processing [23].

The printing technique has a very long history and played a very important role in our civilization. In the past, numerous techniques have been developed for printing, for instance, offset printing, flexography printing, screen printing, inkjet printing, transfer printing, etc. A few of these printing techniques have been modified for liquid alloy patterning on the elastic substrate (Fig. 4). Gallium-based alloys have a very low viscosity, and could therefore be promising for jetting printing (direct printing).

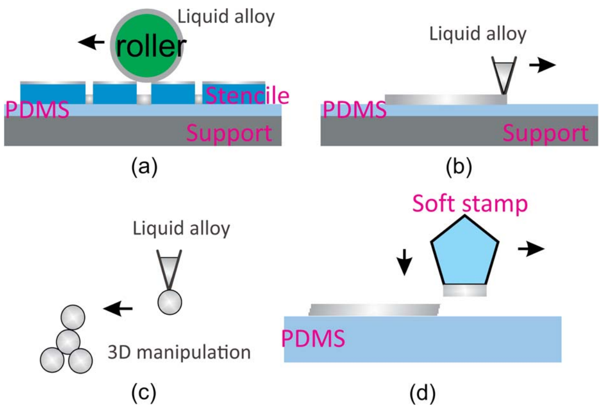


Fig. 4. ***Various printing techniques: (a) stencil printing; (b) direct printing (direct writing); (c) 3-D printing (dispensing); and (d) micro-contact printing.***

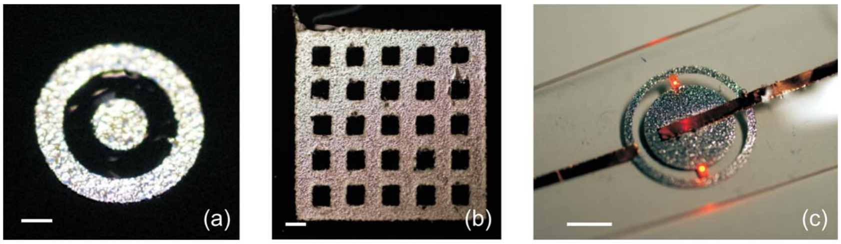


Fig. 5. *Examples of isolated patterns with a tape transfer masking: (a) coaxial circular pattern; (b) rectangular mesh pattern; and (c) LED lighting device with an isolated liquid alloy conductor structure. The scale bar is 1 mm in (a) and (b) and 10 mm in (c).*

Unfortunately, they also have very high surface energy, which means that a strong force is required during processing, which is incompatible with most available inkjet printing equipment. By introducing an automated pneumatic jetting system with a roller pen, direct patterning of liquid alloy circuits on flexible substrates has been demonstrated [34]. This pneumatic drive can be replaced by an ordinary syringe pump system in prototyping [35].

Adapting the traditional printing with a metal stencil mask, a batch type process by deposition of liquid alloy circuits onto an elastic substrate was demonstrated [36]. To bridge the huge mismatch of the surface energy between the liquid alloy and the PDMS substrate and to ease further encapsulation with PDMS, half-curing of PDMS was employed. This makes it easier to print the liquid alloy onto the PDMS substrate. However, the metal mask required all patterns of the mask to be connected and was easily deformed when thin long structures were included in the mask. To overcome these limitations, a transfer technique with an adhesive mask was applied. As it provided both advantages of isolated patterns on a mask and of easy handling, this new masking technique significantly enhanced the versatility of the stencil printing technique [37]. In particular, as shown in Fig. 5, this printing technique with tape transfer masking technique could deposit isolated structures with one step processing, which was not easy to fabricate with a metal stencil mask.

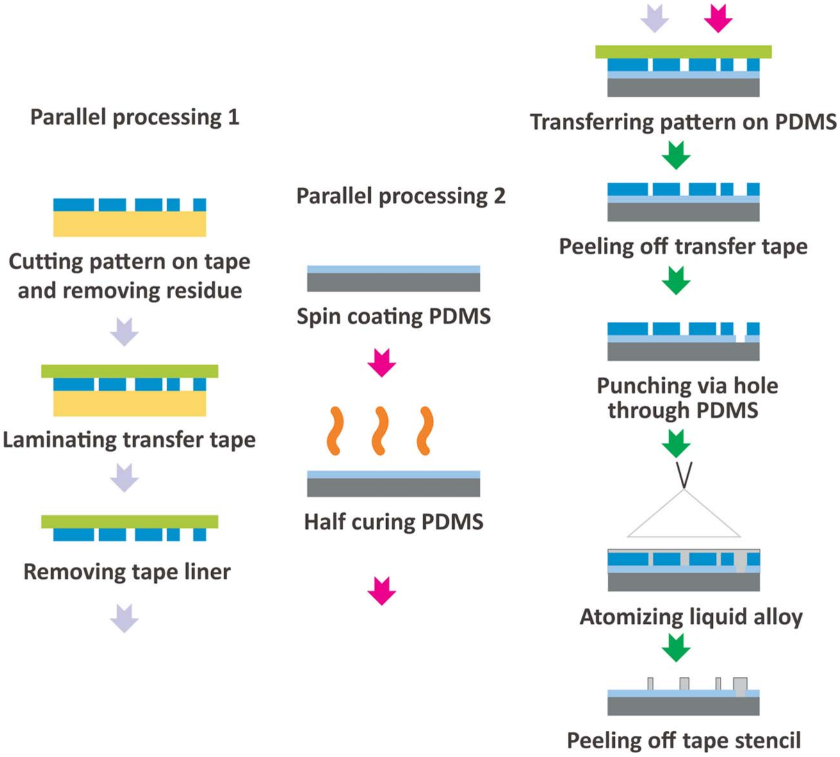


Fig. 6. *Schematic illustration of tape transfer atomized printing of liquid alloys.*

To enhance the deposition quality of the liquid alloy, a further development was made where atomized liquid alloy droplets were sprayed through a tape masked PDMS substrate [38] (Fig. 6). During this process, the liquid alloy droplets gained strong momentum by a pressurized gas flow and the consequent stronger adhesion further extends the versatility of printed substrates. Printing quality has high potential for improvement if dedicated atomization equipment is available. In addition, a lift off concept was also investigated for patterning using a liquid alloy solvable masked stencil technique [39]. Apart from the stencil printing technique, other new forms of printing, such as 3-D printing [40] and microcontact printing [41], have also been investigated recently.

C. Introducing Active Electronics: Device Integration

As mentioned earlier, solid metal thin-film-based stretchable electronics can enable stretchable interconnections as well as active components such as transistors and diodes. Many impressive demonstrations for elastic electronics have been based on ultrathin IC technology and transfer printing. However, it is difficult to make such active components by using the currently existing microfluidic technology. The lack of a monolithic fabrication solution for active components hinders one way of making fully functional microfluidic electronics or systems. However, traditionally hybrid integration has often been used to make advanced systems by assembling modules of various functional parts made by several processes or materials on a carrier or a substrate [5]. Microfluidic stretchable electronics is well suited for such hybrid integration since liquid alloys have high compliance and the liquid contact to rigid components will not break when stretched. Therefore, small footprint, high density, and rigid or flexible active electronics made by traditional IC technology may be sparsely distributed over large area elastic substrates and connected with patterned liquid alloy circuits on the substrate. In such a system, the strain will be first absorbed by the soft and stretchable elastic substrate and hence protect the rigid parts from the mechanical damage caused by stretching. Although some parts of the system are still rigid, the entire device is still stretchable to a large degree. This strategy can be further improved by introducing localized stiff cells (LSCs), with which an integrated microfluidic stretchable RF device was first demonstrated [42] (Fig. 7). Depending on the complexity of the circuit design, the active parts with semiconductor devices could be first integrated onto a small flexible circuit board, or directly assembled on the stretchable passive microfluidic electronic substrate, and then encapsulated to form a completely functional electronic system. The concept of LSC can also be further adapted to multiplayer fabrication either by combining with a liquid alloy filling process [43] or various printing techniques [36].

Since the stretchability of PDMS can be easily tuned by varying the length of the backbone chain or the degree of cross linking, the concept of LSC can be further extended to the material level. One example of photopatterning and mechanical properties of photosensitized PDMS has been demonstrated, with an optically tunable stiffer LSC surrounded by softer PDMS [44]. In addition, LSC could be implemented with a soft siloxane material that offers much higher stretchabilty that is used to encapsulate

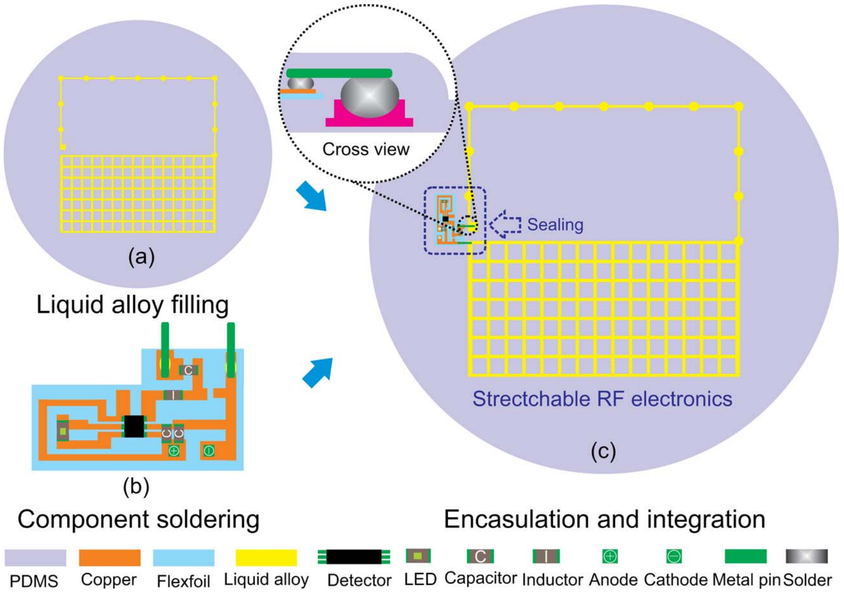


Fig. 7. ***Fabrication process of hybrid integration with an LSC.***

highly stretchable liquid alloy circuits, while another harder siloxane material is stiffer and can be used to surround and protect stiff flexible and even rigid components [45]. Theoretically, this solution should offer high stretchability and reliability. Unfortunately, this soft siloxane has a compatibility problem with PDMS. They do not bond well with each other by traditional plasma treatment. In addition, it is considered to be more difficult to handle than the widely used harder PDMS material. In another approach, polyurethane-based composite has been studied to enhance robust LSC concept [46].

III. DEVICE EXAMPLES

A. Components

As mentioned earlier, mercury was the only highly conductive liquid metal for many years, and it was often used as discrete droplets in many microfluidic applications [47]. Switches are one of them [25]. One of the pioneer works on microfluidic RF devices was to use a Galinstan droplet in a Teflon-based solution to replace mercury in the switch [48] [Fig. 8(a)]. In this design, microfabricated coplanar waveguide (CPW) conductors were made on the substrate and covered by a microfluidic channel made by PDMS. The Galinstan droplet suspending in dielectric Teflon-based solution was subsequently filled in the channel. With pneumatic tuning, the position of the alloy droplet could be precisely controlled to turn the switch on or off. The introduction of the liquid alloy significantly reduced the reflection of the incident power in the on-state, while maintaining the excellent off-state performance at the same time. Technically, the optimal design showed an off-state insertion loss of less than 1.3 dB at 10–40 GHz, on- and off-state return loss of less than 10 dB, and on-state isolation of 27.5 dB at 40 GHz. This droplet configuration can also be scaled to an aligned liquid alloy droplet array between the metallic electrodes (surface) [Fig. 8(b)]. By moving the position of the liquid droplets, the subsequent change of capacitance between the electrodes could be used to tune the working frequency of the surface. Combined with second-order bandpass responses such as nonresonant constituting elements, this approach showed a wider tuning bandwidth in comparison to other liquid-tunable techniques [49].

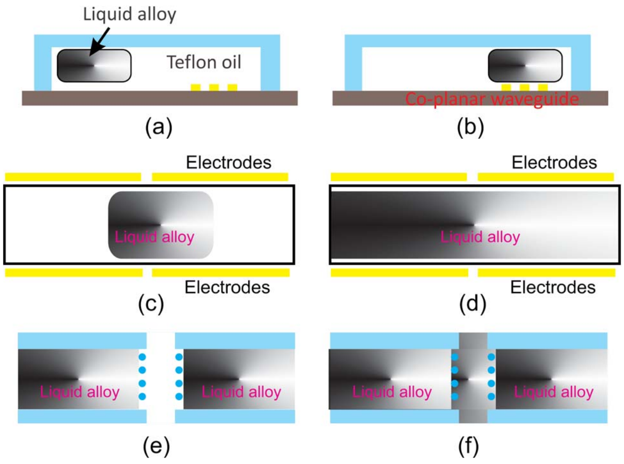


Fig. 8. ***Droplet-based applications: (a) and (b) RF switch; (c) and (d) selective surface; and (e) and (f) frequency shift antenna.***

By filling the highly conductive liquid alloy (Galinstan) into an elastic microfluidic channel, a multi-axially stretchable unbalanced loop antenna at the 2.4-GHz band was the first microfluidic liquid alloy antenna [Fig. 9(a)] [29]. At the relaxed state, the length of the upper radiating arm of the antenna measured 56.4 mm, and the corresponding resonance frequency would be 2.7 GHz. The effective length of the radiating arm increased due to the existence of the liquid alloy reservoirs. According to the antenna theory, assuming that the effective dielectric constant is approximately 1 due to the negligible effect of the thin PDMS membrane, the resonance frequency f of the antenna is determined by the overall length of the upper tube (L) by $f \approx c/2L$. Hence, the actual resonance frequency would decrease accordingly, nearing the designed resonance frequency of 2.4 GHz. When the length of the upper radiating arm of the stretched antenna was stretched further, this led to a lower resonance frequency. Due to the high conductivity of the liquid alloy and large cross-section dimensions of the microfluidic channels, low conductive loss and hence high radiation efficiency of the antenna were observed. Electrical measurements indicated that the radiation efficiency of the antenna at 2.4 GHz was always kept higher than 80% even when stretched up to 40%. Apart from this monopole design, a dipole design was investigated with another gallium-based alloy, which also showed good stretchability [50].

In antennas, resonance frequency is inversely proportional to its physical size. Hence, stretching often leads to lower resonance frequency, which may significantly reduce the antenna performance at a specific frequency. To match this change, the corresponding working frequency of the relevant RF circuits could be tuned accordingly. More practically, a wideband antenna design is preferred in such a situation. Similar to the volcano antenna and the circular disk antenna, the planar inverted cone antenna has also shown a broadband capability and its uniplanar structure is suitable for deformation such as folding, twisting, and stretching. Furthermore, it has an omnidirectional radiation pattern, which is attractive for many mobile applications. Using a leaf-shaped radiator and a large ground plane, a stretchable planar inverted cone antenna with an ultrawideband frequency range of 3.1–10.6 GHz was made by filling the liquid alloy into an elastic channel network [Fig. 9(b)] [30]. The measurements indicated that a good impedance match remained at

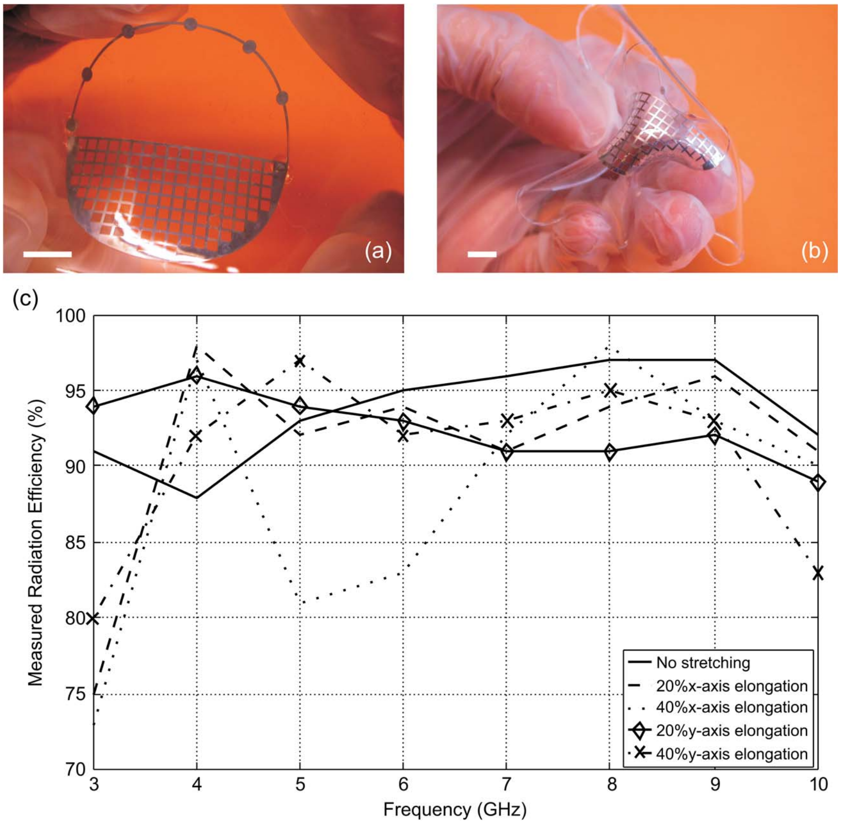


Fig. 9. ***Photos of a stretchable monopole antenna (a), and a broadband antenna (b) and its radiation efficiency when in relaxed and various stretched states (c). The scale bar is 10 mm.***

frequencies higher than 3.4 GHz, even when stretched by 40%. This was also true when radiation patterns at resonance frequencies of 2.5 and 5 GHz were measured in relaxed and stretched (40%) states, respectively. At 2.5 GHz, slight variations in the measured radiation patterns were noted comparing the relaxed and stretched (40%) states. However, no significant gain reduction was observed. At 5 GHz, somewhat larger variations were observed, but still in a reasonable range. As expected, the radiation efficiency measurements in a reverberation chamber indicated that the radiation efficiency at the lower end of the frequency range decreases when the antenna was stretched, but it was still above 70% [Fig. 9(c)].

Usually, when they are exposed to ambient air, gallium-based alloys spontaneously form an oxidized layer that does not grow significantly thicker with time [26]. This oxidized layer significantly affects the surface energy and rheological behavior of the liquid alloy and is hence referred to as an oxide skin. Rheological investigations have indicated that this oxide skin has an elastic nature and yields at a critical stress [47]. By introducing a few aligned postarrays in the channel, the liquid alloy can be divided into a few adjacent segments [Fig. 8(c)], due to the existence of this critical stress. When pressure above this critical stress is applied, the liquid alloy in the vertical direction is pushed in and connects two adjacent segments. The merged liquid alloy then creates an elongated dipole branch, which can shift the resonance frequency of the antenna in a specific way. In their design [51], two aligned postarrays were introduced in each branch of the dipole antenna. Via various permutations, three resonance frequencies could be obtained by pneumatically controlling the merging of the liquid alloy branches.

In the antenna design, a 3-D electrically small antenna (3DESA) is favored in many applications since it sets the limit of the smallest footprint, which is increasingly desirable in portable devices and terminals. Unfortunately, it has been difficult to make a 3DESA using traditional planar fabrication techniques. Recent technical advances make it much easier. For instance, 3-D printing as well as pneumatic pattern transferring was used to make such a 3DESA [52]. However, these 3DESAs suffer from high cost fabrication processes, low radiation efficiency, and very narrow resonance bandwidths. One solution to provide high radiation efficiency and a broad working frequency is to make a small spherical cap ESA, of which the central working frequency can be mechanically tuned. Considering the excellent stretchability of microfluidic liquid alloy circuits, a 3-D cap ESA was made by pneumatically inflating a planar fabricated liquid alloy helix in a highly

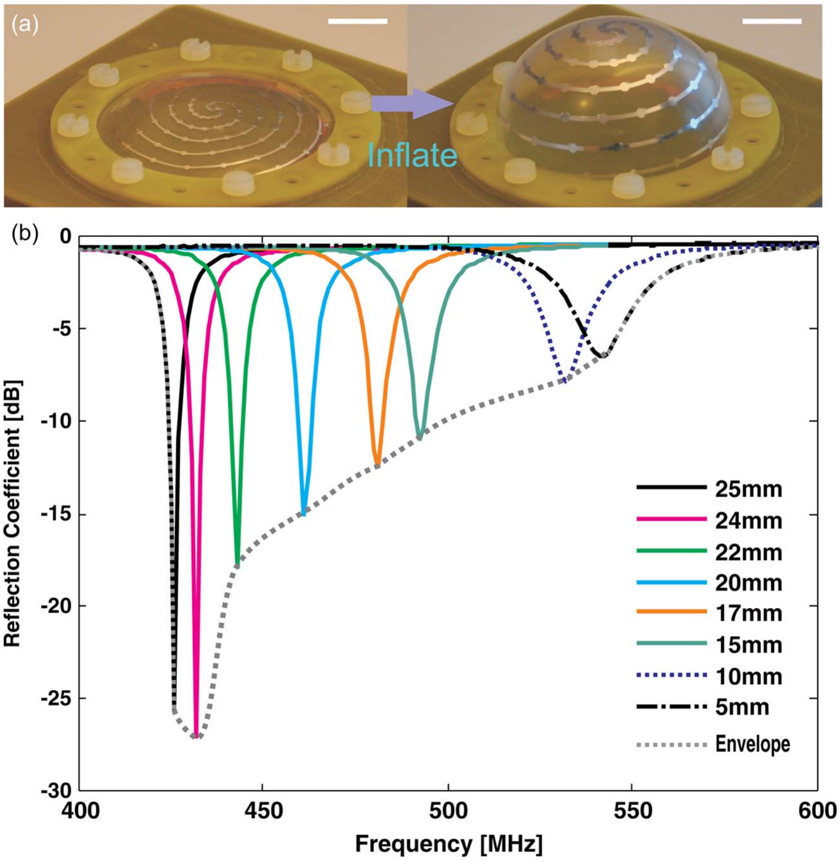


Fig. 10. ***Working principle of a microfluidic tunable 3DESA and its frequency response. The scale bar is 10 mm.***

stretchable siloxane substrate (Fig. 10). The measured results indicated that the central frequency could be tuned in a range of 116 MHz, from 426 to 542 MHz. Correspondingly, the bandwidth within the tunable range went from 8 MHz at 426 MHz to 19 MHz at 542 MHz, with the reflection coefficient of −25.6 and −6.5 dB, respectively. However, the efficiency decreased dramatically when it was close to a planar shape. Still, compared to the stationary bandwidth of 2.4%, the five higher inflation points close to the semispherical cap provided a high efficiency tunable bandwidth of 14.4% (12.4% tunable range and 2% bandwidth at the endpoints).

In addition, since the characterization of the RF system is very sensitive to the surrounding environments, it is necessary to carry out the characterization in a special designed facility such as an anechoic chamber, as we did in the above work [52]. In principle, the behavior of the stretchable antenna can be predicted using an analytical solution or computational simulation such as that in [29], [30], and [52]. In practice, the behavior of a nonstretched antenna was better predicted than that of a stretched one. Most of the reason for this is that the precise deformation of the stretchable antenna is not easy to predict. Still, according to our experience, with more accurate data for the geometrical deformation, the behavior of stretchable antenna before and after stretching can be precisely predicted with computational simulation.

B. Integrated Devices

Today, our bodies are exposed to a world full of various electromagnetic fields (EMFs). It is important to measure these and warn professionals working in risk areas with high exposure levels to the EMFs that may be harmful to human health, and in particular toward specific risk groups such as pregnant women. A soft radiation sensor that could send a warning signal in harmful situations would provide an ergonomic solution. This could be of general interest as the increasing EMFs generated by more and more modern wireless communication systems may cause health concerns for risk groups. By introducing the concept of LSC mentioned above, a hybrid solution was proposed to make a radiation sensor working around 900 MHz [42] (Fig. 11). The demonstrated sensor consisted of three submodules, which were fully embedded in a large areal stretchable substrate: an antenna to receive the energy of RF radiation from the free space, an RF power detection unit to convert the received RF power to the corresponding dc signal, and a light-emitted diode (LED) as an indicator to visualize the

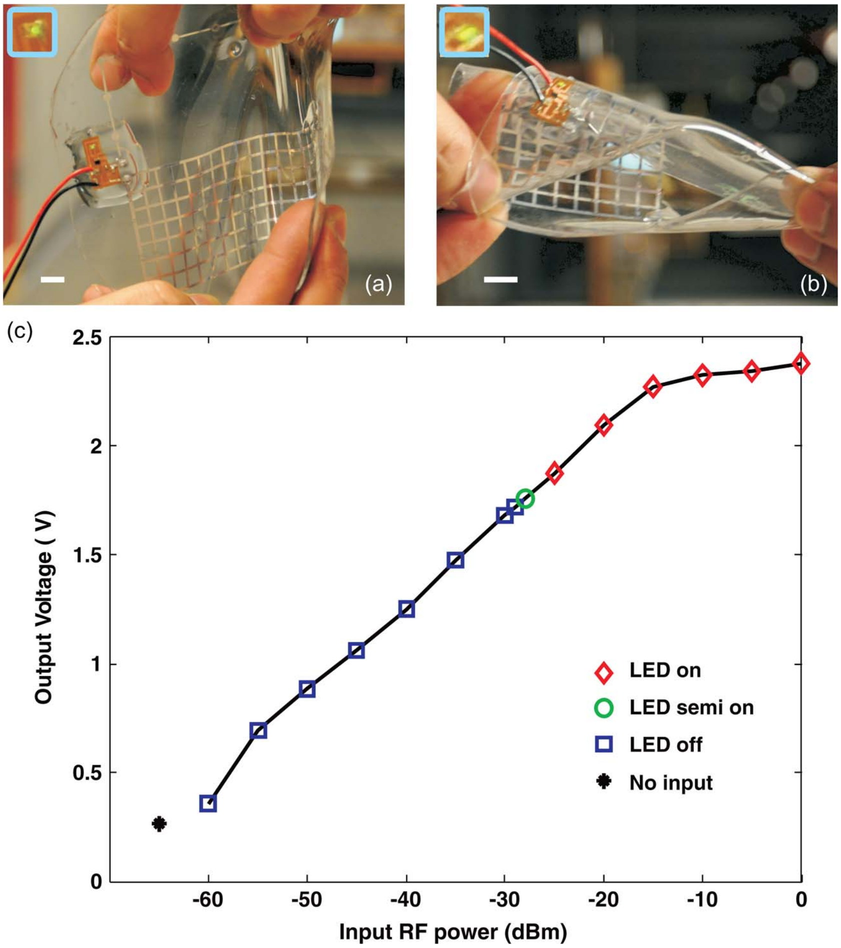


Fig. 11. *Photos of the integrated radiation sensor at difference states and its response curve. The scale bar is 10 mm.*

results of the RF radiation sensing. To simulate the high exposure in the EMF, a horn antenna connected with an RF signal generator was placed at a distance of a few meters from the RF radiation sensor. The experimental data indicated a linear behavior when the RF input varied between −55 and −15 dBm, which means that the relationship between the input RF power and the corresponding output dc voltages could be easily interpolated with careful calibration. In the demonstrated RF power detector, the output voltage of 1.76 V corresponded to an RF input of −28 dBm, which means that when the input RF power was above 28 dBm, the LED indicator remained in its on-state, and *vice versa*. The prototype could detect RF radiation 5 m away, when it was either in a relaxed or stretched state (up to 15% strain).

As they enable remote real-time monitoring of various physiological parameters, e.g., body temperature, heartbeat rates, acceleration, gravity, mechanical strains or motion, self-organized wireless body area networks (WBANs) including multiple wireless sensor nodes are expected to play an essential role in future rehabilitation, athletics training, healthcare, patient monitoring, kids or baby monitoring, and fitness monitoring. However, when working on large curvilinear body surfaces or movable parts, ordinary miniaturized sensor nodes do not work well. Hence, it is necessary to develop new large areal stretchable WBANs, which can offer excellent comfort compared to their wired and rigid counterparts. To demonstrate the possibility of such WBANs, a microfluidic reversibly stretchable large areal wireless strain senor was developed [43]. The senor was fabricated by a multilayer fabrication technique with LSC and dimensions of 110.0 mm × 80.0 mm. The sensor itself consisted of two modules: one voltage controlled oscillator to generate a resonance RF signal and an antenna to transit the RF signal from the oscillator. To monitor the transmitted RF signal from the sensor, a receiver was used. Basically, the design was very similar to the radiation sensor above. The only difference was the converted voltage that was recorded to the computer quantitatively instead of driving an LED qualitatively. When designing the antenna, the central resonance frequency was set to be sensitive to the applied

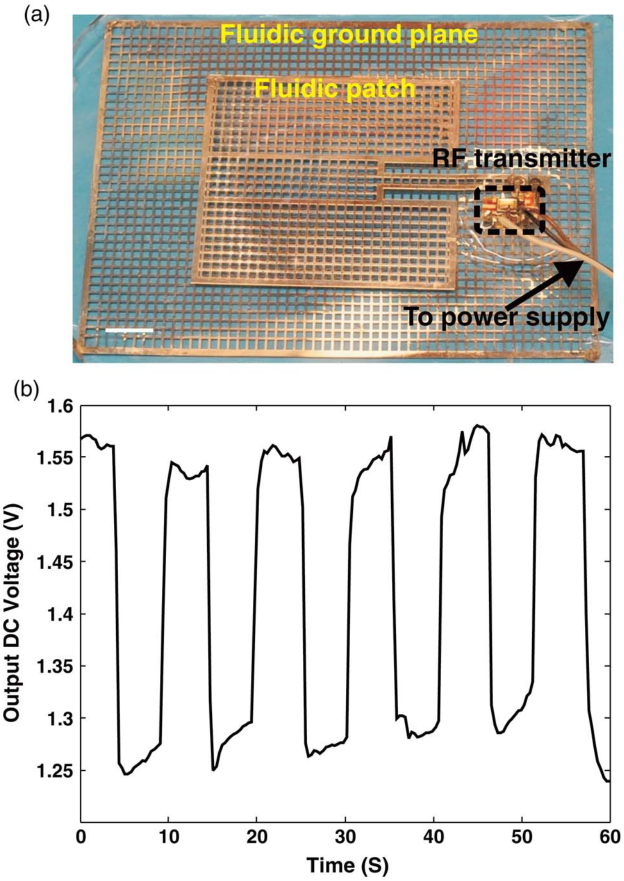


Fig. 12. ***Photo of a large areal strain sensor and its real-time response curve. The scale bar is 10 mm.***

strain on the antenna. Subsequently, this variation of the transmitted RF intensity from the sensor could be tracked by the receiver and recorded by the connected computer simultaneously. By calibrating this response, we could obtain the information on the applied strain by reading the recorded response dc voltage in the receiver. Due to the high fluidity of the liquid alloy, no hysteresis is observed after the removal of an applied strain, which makes it desirable for real-time measurements.

To verify this hypothesis, cycled strains were manually introduced to the integrated sensor at a frequency of around 0.1 Hz. The sensor was first relaxed for 5 s, and then horizontally stretched to about 15% for the remaining 5 s. The output dc voltages responding to the mechanical strains on the sensor were continuously measured by the receiver and finally recorded in a connected computer. The measured voltages varied from 1.55 V initially to approximately 1.28 V as a result of stretching (Fig. 12). The measured results indicated that the demonstrated wireless strain sensor rapidly returned to its original state every time without any observed hysteresis, after the removal of an applied stress. In summary, this kind of integrated sensor with a mechanically reconfigurable antenna not only senses large-areal high tensile strains but also transmits the results wirelessly in real time. More importantly, apart from large areal measurements, it removes the need for hard wiring to any external instruments, which severely reduces convenience in daily life when being attached to the human body. To conclude, by using microfluidic RF technology, this sensor demonstrated a new possibility of creating more ergonomic WBAN sensor nodes for wearable electronics.

Today, with computing costs continually decreasing, large amount of data generate more interest in wireless sensors in wearable electronics and home appliances connected to the Internet of Things. In particular, it will be more attractive to introduce this kind of sensor to WBANs when they need to be in contact with our body. One of the most essential functions of such a sensor is identity. By using a batch fabrication technique, a stretchable ultra-high-frequency radio-frequency identity (UHF RFID) tag was demonstrated [36] (Fig. 13). It could be read at a distance of up to 13.95 m in ambient air, both in relaxed and stretched states (up to 20%). Moreover, the mechanical stretching test showed that it could survive above 1000 stretching cycles without any significant mechanical or electrical degrading. Connected to the earlier discussion in Section II, an improved fabrication process was later proposed to make a similar tag. Compared to the

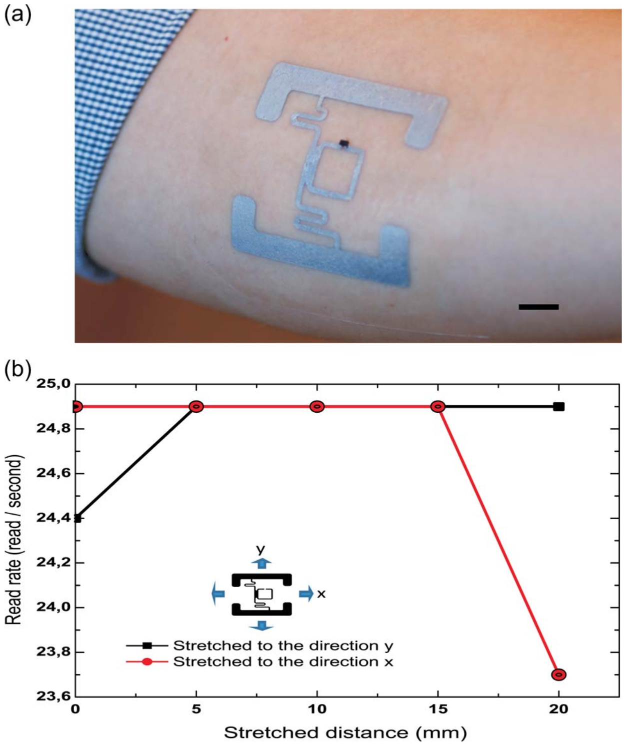


Fig. 13. ***Photo of a stretchable RFID and its measured read rates. The scale bar is 10 mm.***

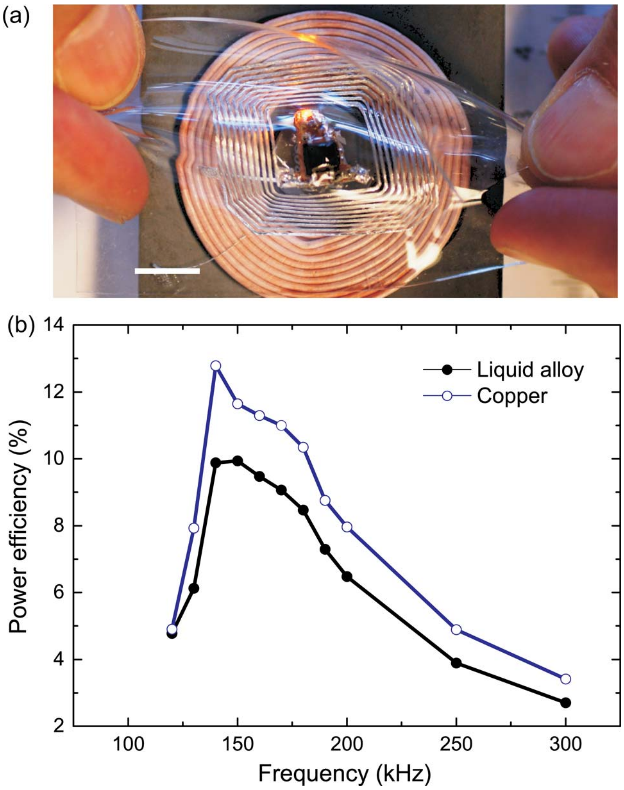


Fig. 14. ***Photo of a working stretchable wireless power transfer device and the measured power efficiency with a reference copper foil. The scale bar is 10 mm.***

reference tag from the supplier, this microfluidic-based stretchable RFID demonstrated excellent performance at 50% strain [37].

As mentioned earlier, one of the most attractive features of stretchable/conformal electronics is compliant wireless sensor systems such as WBAN. Like any other portable devices or systems, the bottle neck is the power supply with its relevant storage devices such as batteries and super capacitors, and various energy harvesters such as solar cells. Making these devices stretchable also presents huge technical challenges. For instance, today's WBAN sensing system based on rigid and flexible materials has a battery that is bulky and heavy, and still has limited capacity (service time). This is not acceptable in stretchable/conformal electronics. Hence, the power supply module is the largest obstacle to overcome before achieving fully integrated conformal systems on or in the human body. Employing the newly developed fabrication technique discussed in Section II, a stretchable wireless power transfer device that could survive cycling between 0% and 25% strain over 1000 times was demonstrated for the first time with an atomized liquid alloy circuit on a PDMS substrate [38]. Owing to the high conductance of the liquid alloy and a newly introduced reliable fabrication technique, the fabricated coil showed low resistance around 8.1 Ω, which was a 600-μm-wide, 120-μm-thick, and 82-cm-long coil. This was the first time such a long line with such high conductance has been made based on a liquid alloy. Even compared to the similar sized reference coil made by copper, the microfluidic enabled coil performed reasonably well (Fig. 14). Further improvement and optimization of this kind of technology will create new opportunities to make self-contained, fully functional conformal devices or intelligent systems on the skin or as implants, for man–machine communication.

IV. DISCUSSION

Due to excellent electrical conductivity and high stretchability, microfluidic RF electronics has shown high potential in creating conformal autonomous smart devices that are targeted to applications on the human body. However, as an emerging field, it has a lot of challenges that need to be solved. Some of these issues, such as liquid alloy manipulation and integration, contacts to solid metals, new conductive materials, and long-term reliability investigation, have been discussed elsewhere [23]. Here, our intentions were to present more recent results and to focus on microfluidic stretchable RF electronics.

Antennas have been the most investigated stretchable RF components. There are good reasons for this. 1) Antennas are sensitive to electric conductance and liquid alloys provide comparably good conductivity in bulk, and the microfluidic technique allows for larger cross sections when stretched compared to other techniques. 2) Antennas are size-sensitive components and in particular, to ensure high-quality signals, large sizes are required for body area applications, where high stretchability is naturally demanded. However, our skin is a complex and dynamic organ, which strongly interacts with devices that work on it. This will significantly influence the performance of the device and even lead to device failure in practical situations. Introducing a large metal ground to a patch antenna isolates the antenna from such negative influences. Unfortunately, the relatively thick structure makes it less compliant and will negatively affect the user experience. Hence, a comprehensive study is required to optimize the design to balance the performance and user experience or to introduce a totally new design targeting stability and high performance of antennas as well as good user experience. In addition, although antennas were the most investigated microfluidic stretchable RF components, there are still many blank areas waiting for us to explore, e.g., radiation pattern reconfigurable antennas and antenna arrays. Furthermore, apart from antennas, some other RF passive components, such as transmission lines, have been rarely studied, although they could benefit from the application of this soft and reconfigurable technique.

Microfluidic stretchable RF components bring new possibilities of expanding analog to active hardware for reconfigurable systems. In many potential applications, low energy and small footprint active circuits are essential and critical components. However, the corresponding optimized RF circuits have still not been investigated extensively in combination with the stretchable RF systems. Of course, energy conversion and storage devices, such as various energy harvesters and batteries, are important components which limit the performance of portable devices, and need to receive more attention. In addition, on a system level, the optimization of electrical and mechanical performance as well as of energy consumption is necessary. Once again, to our understanding, no such work has been reported in stretchable RF electronics.

For every new technology, a very important perspective is to encourage more people to engage in the field and to work from different perspectives and explore new applications. As we demonstrated above, one of the most attractive applications for this soft RF technique is wearable systems. However, this does not exclude other applications. For instance, as a conformal technique, it could be used in large areal applications such as in surface antenna on aircraft and satellites, in structure health monitoring on complex surfaces such as heavy machinery or wings of an airplane, or in monitoring systems with a curved surface such as autonomous sensing balls floating in the sea or thrown out from a helicopter in an emergency or a dangerous scenario such as in wild fires. Or it could be used in reconfigurable reflective surfaces, metamaterials, and reflective radar systems. A niche application that could fully exploit the advantages of microfluidic stretchable RF electronics and demonstrate incomparable performance or user experience would significantly accelerate the development of this research field.

V. CONCLUSION

Coupling the inherent fluidity and excellent electrical performance of a liquid alloy with hybrid integration of modular functional parts on stretchable elastic substrates, microfluidic stretchable RF electronics has an incomparable performance in wireless applications. It has a high possibility of strongly impacting the applications where ergonomically or conformal design of complex surfaces is sought, for example, sensor skins for robotics, wearables, and implantable electronics, and aerospace communication systems. The never-ending demand for improved user experience and for wireless communication will give us the historical chance to create a brand new market with soft RF electronics and even overturn peoples' opinion of electronics and reshape their daily lives. However, current understanding is not ready to support a future technical revolution. The challenges demand talented contributions from researchers with different backgrounds, and in particular, from electronic and software engineers. ■

REFERENCES

[1] G. E. Moore, "Cramming more components onto integrated circuits," *Electronics*, vol. 38, pp. 4–7, 1965.

[2] "2013 represented worst decline in PC market's history," *Forbes*, last Accessed Aug. 31, 2014. [Online]. Available: http://www.forbes.com/sites/jasonevangelho/2014/01/09/2013-represented-worst-decline-in-pc-markets-history/

[3] R. K. Cavin, P. Lugli, and V. V. Zhirnov, "Science and engineering beyond Moore's law," *Proc. IEEE*, vol. 100, no. Special Centennial Issue, pp. 1720–1749, May 13, 2012.

[4] G. Q. Zhang and A. Roosmalen, *More than Moore*. Dordrecht, The Netherlands: Springer-Verlag, 2009.

[5] W. S. Song and A. Salleo, *Flexible Electronics: Materials and Applications*. New York, NY, USA: Springer-Verlag, 2009.

[6] J. A. Rogers, T. Someya, and Y. Huang, "Materials and mechanics for stretchable electronics," *Science*, vol. 327, no. 5973, pp. 1603–1607, 2010.

[7] S. Wagner and S. Bauer, "Materials for stretchable electronics," *MRS Bull.*, vol. 37, no. 3, pp. 207–213, 2012.

[8] J. A. Rogers, "Materials for semiconductor devices that can bend, fold, twist, and stretch," *MRS Bull.*, vol. 39, no. 6, pp. 549–556, 2014.

[9] T. Someya, *Stretchable Electronics*. Weinheim, Germany: Wiley, 2014.

[10] D.-H. Kim *et al.*, "Materials for multifunctional balloon catheters with capabilities in cardiac electrophysiological mapping and ablation therapy," *Nature Mater.*, vol. 10, pp. 316–323, 2011.

[11] H. C. Ko *et al.*, "A Hemispherical electronic eye camera based on compressible silicon optoelectronics," *Nature*, vol. 454, pp. 748–753, 2008.

[12] D.-H. Kim *et al.*, "Epidermal eletronics," *Science*, vol. 333, no. 6044, pp. 838–843, 2011.

[13] D. C. Duffy, J. C. McDonald, O. J. A. Schueller, and G. M. Whitesides, "Rapid prototyping of microfluidic systems in poly(dimethylsiloxane)," *Anal. Chem.*, vol. 70, pp. 4974–4984, 1998.

[14] Y. Xia and G. M. Whitesides, "Soft lithography," *Annu. Rev. Mater. Sci.*, vol. 28, pp. 153–184, 1998.

[15] J. El-Ali, P. K. Songer, and K. F. Jensen, "Cells on chips," *Nature*, vol. 442, pp. 403–411, 2006.

[16] R. Mukhopadhyay, "When PDMS isn't the best," *Anal. Chem.*, vol. 79, no. 9, pp. 3248–3253, 2007.

[17] A. C. M. Kuo, "Poly(dimethylsiloxane)," in *Polymer Data Handbook*. Oxford, U.K.: Oxford Univ. Press, 1999.

[18] N. Bowden, S. Brittain, A. G. Evans, J. W. Hutchinson, and G. M. Whitesides, "Spontaneous formation of ordered structures in thin films of metals supported on an elastomeric polymer," *Nature*, vol. 393, pp. 146–149, 1998.

[19] S. P. Lacour, S. Wagner, Z. Y. Huang, and Z. G. Suo, "Stretchable gold conductors on elastomeric substrates," *Appl. Phys. Lett.*, vol. 82, pp. 2404–2406, 2003.

[20] S. P. Lacour, J. Jones, S. Wagner, T. Li, and Z. G. Suo, "Stretchable interconnects for elastic electronic surfaces," *Proc. IEEE*, vol. 93, no. 8, pp. 1459–1467, Aug. 2005.

[21] Y. Sun, W. M. Choi, H. Jiang, Y. Huang, and J. A. Rogers, "Controlled buckling of semiconductor nanoribbons for stretchable electronics," *Nature Nanotechnol.*, vol. 1, pp. 201–207, 2006.

[22] D.-H. Kim *et al.*, "Materials and noncoplanar mesh designs for integrated circuits with linear elastic responses to extreme mechanical deformations," *Proc. Nat. Acad. Sci. USA*, vol. 105, no. 48, pp. 18 675–18 680, 2008.

[23] S. Cheng and Z. G. Wu, "Microfluidic electronics," *Lab Chip.*, vol. 12, pp. 2782–2791, 2012.

[24] J. Simon, S. Saffer, and C.-J. Kim, "A liquid-filled microrelay with a moving mercury microdrop," *J. Microelectromech. Syst.*, vol. 6, no. 3, pp. 208–216, 1997.

[25] P. Sen and C.-J. Kim, "Microscale liquid-metal switches—A review," *IEEE Trans. Ind. Electron.*, vol. 56, no. 4, pp. 1314–1330, Apr. 2009.

[26] T. Liu, P. Sen, and C.-J. Kim, "Characterization of nontoxic liquid-metal alloy Galinstan for applications in microdevices," *J. Microelectromech. Syst.*, vol. 21, no. 3, pp. 443–450, 2011.

[27] N. B. Morley, J. Burris, L. C. Cadwallader, and M. D. Nornberg, "GaInSn usage in the research laboratory," *Rev. Sci. Instrum.*, vol. 79, 2008, Art. ID. 056107.

[28] T. Sekitani *et al.*, "A rubberlike stretchable active matrix using elastic conductors," *Science*, vol. 321, no. 5859, pp. 1468–1472, 2008.

[29] S. Cheng, A. Rydberg, K. Hjort, and Z. G. Wu, "Liquid metal stretchable unbalanced loop antenna," *Appl. Phys. Lett.*, vol. 94, 2009, Art. ID. 144103.

[30] S. Cheng, Z. G. Wu, P. Hallbjörner, K. Hjort, and A. Rydberg, "Foldable and stretchable liquid metal planar inverted cone antenna," *IEEE Trans. Antennas Propag.*, vol. 57, no. 12, pp. 3765–3771, Dec. 2009.

[31] H.-J. Kim, T. Maleki, P. Wei, and B. Ziaie, "A biaxial stretchable interconnect with liquid-alloy-covered joints on elastomeric substrate," *J. Microelectromech. Syst.*, vol. 18, pp. 138–146, 2009.

[32] A. Fassler and C. Majidi, "3D structures of liquid-phase GaIn alloy embedded in PDMS with freeze casting," *Lab Chip*, vol. 13, pp. 4442–4450, 2013.

[33] J. Park *et al.*, "Three-dimensional nanonetworks for giant stretchability in dielectrics and conductors," *Nature Commun.*, vol. 3, p. 916, 2012.

[34] Y. Zheng, Q. Zhang, and J. Liu, "Pervasive liquid metal based direct writing electronics with roller-ball pen," *AIP Adv.*, vol. 3, 2014, Art. ID. 112117.

[35] J. W. Boley, E. L. White, G. T.-C. Chiu, and R. Kramer, "Direct writing of gallium-indium alloy for stretchable electronics," *Adv. Funct. Mater.*, vol. 24, pp. 3501–3506, 2014.

[36] S. H. Jeong *et al.*, "Liquid alloy printing of microfluidic stretchable electronics," *Lab Chip.*, vol. 12, pp. 4657–4664, 2012.

[37] S. H. Jeong, K. Hjort, and Z. G. Wu, "Tape transfer printing of a liquid metal alloy for stretchable RF electronics," *Sensors*, vol. 14, pp. 16 311–16 321, 2014.

[38] S. H. Jeong, K. Hjort, and Z. G. Wu, "Tape transfer atomisation patterning of liquid alloys for microfluidic stretchable wireless power transfer," *Sci. Rep.*, vol. 5, 2015, Art. ID. 8419.

[39] R. K. Kramer, C. Majidi, and R. J. Wood, "Masked deposition of gallium-indium alloys for liquid-embedded elastomer conductors," *Adv. Func. Mater.*, vol. 23, no. 42, pp. 5292–5296, 2013.

[40] A. Tabatabai, A. Fassler, C. Usiak, and C. Majidi, "Liquid-phase gallium–indium alloy electronics with microcontact printing," *Langmuir*, vol. 29, pp. 6194–6200, 2013.

[41] C. Ladd, J-.H. So, J. Muth, and M. D. Dickey, "3D printing of free standing liquid metal Microstructures," *Adv. Mater.*, vol. 25, no. 36, pp. 5081–5085, 2013.

[42] S. Cheng and Z. G. Wu, "Microfluidic stretchable RF electronics," *Lab Chip.*, vol. 10, pp. 3227–3234, 2010.

[43] S. Cheng and Z. G. Wu, "A microfluidic, reversibly stretchable, large-area wireless strain Sensor," *Adv. Funct. Mater.*, vol. 21, no. 12, pp. 2282–2290, 2011.

[44] D. P. J. Cotton, I. M. Graz, and S. P. Lacour, "Photopatterning the mechanical properties of polydimethylsiloxane films," *J. Appl. Phys.*, vol. 109, 2011, Art. ID. 054905.

[45] M. Kubo *et al.*, "Stretchable microfluidic radiofrequency antennas," *Adv. Mater.*, vol. 22, no. 25, pp. 2749–2752, 2010.

[46] R. Libanori *et al.*, "Stretchable heterogeneous composites with extreme mechanical gradients," *Nature Commun.*, vol. 3, p. 1265, 2012.

[47] M. D. Dickey *et al.*, "Eutectic gallium-indium (EGaIn): A liquid metal alloy for the formation of stable structures in microchannels at room temperature," *Adv. Func. Mater.*, vol. 18, no. 7, pp. 1097–1104, 2008.

[48] C.-H. Chen and D. Peroulis, "Liquid RF MEMS wideband reflective and absorptive switches," *IEEE Trans. Microw. Theory Tech.*, vol. 55, no. 12, pp. 2919–2929, Dec. 2007.

[49] M. Li, B. Yu, and N. Behdad, "Liquid-tunable frequency selective surfaces," *IEEE Microw. Wireless Compon. Lett.*, vol. 20, no. 8, pp. 423–425, Aug. 2010.

[50] H.-J. Koo, J.-H. So, M. D. Dickey, and O. Velev, "Towards all-soft matter circuits: Prototypes of quasi-liquid devices with memristor characteristics," *Adv. Mater.*, vol. 23, pp. 3559–3564, 2011.

[51] M. R. Khan, G. J. Hayes, J.-H. So, G. Lazzi, and M. D. Dickey, "A frequency shifting liquid metal antenna with pressure responsiveness," *Appl. Phys. Lett.*, vol. 99, 2011, Art. ID. 013501.

[52] M. Jobs, K. Hjort, A. Rydberg, and Z. G. Wu, "A tunable spherical cap microfluidic electrically small antenna," *Small*, vol. 9, no. 19, pp. 3230–3234, 2013.

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