Fabrication and characterization of aluminum thin film heaters and temperature sensors on a photopolymer for lab-on-chip systems


A R T I C L E   I N F O
Article history:
Received 23 November 2012
Received in revised form 14 January 2013
Accepted 15 January 2013
Available online xxx

Keywords:
Aluminum
Polymer
Heater
Sensor
KMPR
Adhesion

A B S T R A C T
Polymers offer many advantageous physical properties as structural materials for MEMS and microfluidics. Additionally, polymers support rapid and inexpensive fabrication methods. Patterning metals on polymer microstructures is, however, much more challenging than doing so on conventional substrates such as silicon or glass. As a result, metal layers within polymeric devices are typically fabricated on non-polymeric substrates, and the polymer layers are then fabricated on top, which greatly constrains the variety of structures that can be built. A wider range of devices could be fabricated if there was a reliable method for producing and patterning stable metal films on a photo-polymer. Lab-on-chip (LOC) systems in particular would benefit from low-cost, corrosion-resistant, thermally stable metal films embedded in polymer structures. To date, however, there have been no demonstrations that combine all of these characteristics. We present here a method for patterning a film of aluminum on the photopolymer KMPR and treating the film to stabilize its resistivity. We demonstrate the production and stability of the films and demonstrate that they are suitable for use as heaters and/or temperature sensors at temperatures up to 165°C – well beyond the required temperatures for mainstream LOC functions such as the polymerase chain reaction (PCR).

© 2013 Elsevier B.V. All rights reserved.

1. Introduction

Microfluidic technologies are quickly developing around polymers due to the low cost and ease of processing of these materials [1]. Moreover, the low thermal conductivity of polymers can substantially reduce device power consumption. Indeed, many state of the art LOC systems employ polymers as structural materials [2–4]. Further development of affordable lab-on-chip (LOC) technologies demands low cost, stable metal films that can be integrated in polymer structures without difficulty. Many polymeric LOC devices require resistive metal films that can operate at elevated temperatures. However, metallization is generally performed on a glass or silicon substrate, not directly on the polymer, and this limits the functionality and design of these devices.

Metallization on polymers is a challenging process. Polymers are often vulnerable to attack by the organic solvents and developers used in wet processing, often leading to the detachment of the metal film from the polymer [5]. PDMS (polydimethylsiloxane), one of the most commonly used polymers in LOC systems, swells when exposed to most common solvents [1], preventing metal films on their surface from being patterned by standard lithography. Techniques such as microstenciling can be used to pattern metal films onto polymers (such as polyethylene, polystyrene, polycarbonate, polymethyl methacrylate (PMMA), and polylamide), but for some, like PMMA, adhesion to metals is poor [6], and most of them are not photo-patternable. In addition to the difficulty of patterning, metal films on polymers are prone to cracking due to the polymer’s flexibility. For instance, Au/Cr tracks patterned on PDMS will crack and lose conductivity irreversibly when the PDMS is strained by 10% [7]. Metal cracking may also be caused by the large difference in the coefficient of thermal expansion (CTE) of polymers and metals. SU-8 and PMMA, for example, have CTE of 52–150 ppm/K [8] and 90–162 ppm/K [9], respectively, while inorganic substrates, e.g. Si and borosilicate glass have CTE of 2.5 ppm/K [9] and 3.7 ppm/K [10], respectively. For thin film heaters this CTE mismatch is even more critical, and there is the additional constraint of the low glass transition and melting/decomposition temperatures of common polymers.

Using techniques other than lithography, mechanically stable Au features have been patterned through an SU-8 stencil on PDMS [7] or pre-patterned on Si and then embedded in PDMS [11], but their use as heaters or temperature sensors was not demonstrated.
Similarly, Pt/Ti heaters were stencil-patterned on SU-8 for microgrippers [12] and pre-patterned Au/Cr heaters were adhered to SU-8 for microgrippers [13] and for a dermal patch [14].

Commercial polyimide foils, e.g. DuPont’s™ Kapton®, are thermally stable [15], so they are readily used to produce flexible heaters. As manufactured, these foils are not suitable for building integrated heaters and temperature sensors in LOC systems, because they contain intrinsic and extrinsic contaminants that cannot be completely removed by cleaning [15]. These contaminants produce surface peaks tens to hundreds of nanometers high, with frequency of about 1–10 per cm² for peak sizes of 100–200 nm [15], which is typically the thickness of an integrated heater/sensor. The handling of thin foils also presents an issue of distortion due to mechanical stress. Attaching the foil with an adhesive or vacuum to a rigid carrier can help prevent deformation of the foil. Thermal processing such as resist baking in lithography, however, may result in shrinkage [15], and the deposition of metal tends to create compressive stresses [16,17] that may wrinkle the foil or delaminate it from the carrier. Kapton® is metallized (e.g. DuPont’s™ Pyralux®) either by Cu electroplating or by bonding a rolled Cu foil to Kapton® with an acrylic adhesive [18]. Although electroplating can be applied to the fabrication of LOC devices, it may significantly complicate the process. Pyralux® is designed for low resistance electronic interconnects, so its Cu layer is thick (≥9 μm) [18]. Thus, patterning the metal will leave a varied topography that makes difficult the bonding/deposition of subsequent layers in multilayer thin structures. Any suitable thin metal may easily crack due to bending or tension in the foil. In the case of Cu, thin films might be very susceptible to oxidation, and hence destruction. Kapton® has additional disadvantages of not being photo-patternable and requires adhesives for bonding [17,18], and these may trap air bubbles. Bubbles in turn may introduce significant temperature gradients, since air is a strong thermal insulator, with thermal conductivity of 0.026 W/m-K at 300 K, 1 bar [19].

In the LOC field there have been few examples of polymer metallization. Heaters were fabricated on Kapton® by sputtering a Ti/Pt film on top of the polymer [17]. However, patterning required micro-milling and stresses in the Pt film caused detachment from the Kapton®. Conductive compounds with good adhesion to polymers, such as a stencil-printed silver-filled epoxy, have been used as an alternative to metals [5], but these materials cannot replace metals in high performance heating and temperature sensing applications at elevated temperatures. Polymers like cyclic olefin copolymer (COC) withstand polar solvents such as acetone [1] (used to strip photoresists), allowing for metals to be patterned on top by standard lithography. Geiger et al. [1] fabricated COC microfluidic chips by injection molding with Au heaters patterned directly on the polymer by lithography, using either a Cr layer or an O₂ plasma treatment to promote adhesion of Au to the COC. The heaters were operated at 30–40 °C, however a typical LOC system requires heater stability above 100 °C to perform PCR.

For PCR applications, thin film Pt has been used for heaters and sensors in chips made using SU-8 [20] and PDMS [21,22], but the metal was patterned on glass and does not form part of the polymer structure. Alternatives like indium tin oxide (ITO) on glass have also been used for PCR [23,24], but Pt is by far the most widely used material due to its high resistivity, high temperature coefficient of resistivity (TCR), linearity and resistance to corrosion. Pt is extremely expensive, however, requires a Ti or Cr adhesion layer, and must be patterned by lift-off [25] stenciling, or wet etch in boiling *aqua regia* [22], presenting undesirable processing conditions. Furthermore, Pt must be annealed at temperatures higher than the operation temperature for the stabilization of its resistivity [26,27], which can cause problems for the underlying polymer structure including loss of mass [28]. All these factors complicate the incorporation of Pt in a polymer LOC process.

KMPR is a photoresist developed by MicroChem Corp. that has been used as a structural material in LOC devices [29–31]. KMPR has much higher moisture resistance than SU-8 [32], which makes it better suited for LOC devices. KMPR has also been reported to have stronger adhesion to Al than to other metals, such as Cu or Au, and this adhesion increases with a hard-bake [32]. Thus, Al is a good candidate for metallization of KMPR-based LOC systems. Besides good adhesion properties, Al is inexpensive, can be easily patterned by standard lithography, stenciling or lift-off and exhibits low residual stress [33]. Al also forms a highly stable surface passivation oxide that stops corrosion [34]. We believe that the fabrication of highly integrated LOC systems and their adaptation to CMOS technologies is possible using KMPR as a structural material and Al as a metallization material.

Al has previously been patterned on SU-8 and KMPR by lift-off for use as an electrode [32,33], and deposited on SU-8 for use as a sacrificial material [14]. An aluminum heater has also been formed on SU-8 by stenciling for microactuator applications [35]. Although this demonstrated that Al can adhere to an epoxy-based photopolymer under Joule heating conditions, the temperature reached, resistivity and stability of the heater were not reported. In a typical geometry of a LOC system for genetic analysis, heater temperatures need to be precisely controlled and must reach above 100 °C in order to obtain PCR temperatures in the microreactor (60–95 °C).

To our knowledge, in the LOC field there has been no demonstration of a stable heater on photopolymer capable of reaching more than 100 °C. The use of Al for integrated heating and sensing in this field has been hindered by the difficulties of polymer metallization as well as the high susceptibility of Al to electromigration at relatively low current densities, a problem that is exacerbated by Joule heating [36]. The electromigration resistance of Al can be increased up to 10 times by adding Cu in a small percentage [37], however Al–Cu alloys offer little protection to corrosion as they form weak or unstable self-passivating oxides [34,38]. Furthermore, the resistivity of Al is lower than for Pt [19], which might reduce the performance of heaters and sensors.

Previously we demonstrated a multilayer bonding process to build complex KMPR structures [39]. We also recently measured the important structural characteristics of KMPR [28]. This work represents the next step in our effort to build inexpensive and reliable, polymer-based LOC systems for genetic analysis.

We demonstrate for the first time an affordable, stable, non-noble thin film fabricated on a photopolymer that can be used as a heater or temperature sensor in a wide array of thermal operations in LOC systems, including PCR. The stability of the film is demonstrated by the ongoing characterization of its resistivity and TCR in the range of 22–165 °C, and the exceptional adhesion of Al on KMPR is qualitatively verified.

### 2. Fabrication

We produced an Al film on KMPR and patterned heater rings of 1.15 mm inner radius and 100 μm width as follows.

#### 2.1. KMPR layer fabrication

A square 10 cm Borofoil® glass substrate was immersed in fresh 1:3 piranha solution of 30% H₂O₂ and 96% H₂SO₄ for 20 min. After rinsing in water and drying in N₂, the substrate was dehydrated at 150 °C for 10 min in a vacuum oven (YES-310D, Yield Engineering Ltd.). KMPR 1025 (MicroChem Corp., Newton, MA, USA) was allowed to settle for 1 h at room temperature prior to spin coating (Spinner P6700, Headway Research Inc.) on the substrate at 500 rpm for 5 s (100 rpm/s ramp), and then at 1000 rpm for 60 s.
(300 rpm/s ramp) to form a 50 μm layer. The substrate was then soft-baked for 20 min at 105 °C, followed by a blanket UV exposure with a 1000 ml/cm² dose (calculated using the intensity at 365 nm). The film was then cross-linked by baking at 105 °C for 3 min and then at 130 °C for 30 min.

2.2. Aluminum deposition

We sputtered onto the KMPR film a 200 nm metal layer containing Al (and oxide) from an Al target (purity 99.9995%) in a chamber with a significant base pressure (i.e., we expected a significant degree of oxygen incorporation in the form of oxides). By adding moderate amounts of oxygen, we aimed to produce a film of higher resistivity, without risking rendering the film dielectric. A higher resistivity film allows for higher power output per unit current, as well as higher sensitivity when used as a sensor. To achieve this, the chamber of our magnetron sputtering system (1998, Kurt J. Lesker Co.), was pumped down to a base pressure of 1.4 μm Torr prior to initiating sputtering with an Ar gas feed. During sputtering, we held a 7 mTorr deposition pressure by setting 30 sccm Ar flow rate, and used 300 W, 380 V deposition power and voltage, to deposit 7 nm/min.

2.3. Aluminum lithography

10 ml of HPR-504 positive photoresist (OCG Microelectronic Materials Inc., Glasgow, Scotland) was allowed to settle for 20 min at room temperature before being spun onto the Al film at 500 rpm for 10 s, then at 4000 rpm for 40 s to obtain a ∼3 μm film. A soft-bake followed at 115 °C for 15 min in a forced air flow oven (LDX1-42-2, Despatch Industries). The resist was then re-hydrated by leaving it in a closed box with a wet cloth for 15 min prior to UV exposure through a mask with a 180 ml/cm² dose (365 and 405 nm). The resist was developed in Microposit™ 354 (Shipley Inc.) for 15 s, rinsed in water and hard-baked at 115 °C for 120 s. The AI film was etched for 6 min at a rate of ∼35 nm/min, in a 1:6:1:1:2 solution of phosphoric acid, nitric acid, acetic acid and water. The positive resist was stripped in acetone for 10 s.

3. Experimental

We analyzed the behavior of the AI film on KMPR and determined its resistivity characteristics by calibrating the heater’s electrical resistance vs. absolute temperature and then subjecting the heaters to significant Joule heating. This process was carried out twice, and the Joule heating hold time was increased substantially in the second test.

3.1. Calibration

The aluminum heater-on-KMPR chips were clamped in a holder equipped with round-tip spring-loaded Au-coated “pogo” pins of 1 mm diameter (Interconnect Devices Inc.), which make contact with the heater terminals without scratching the metal. The holder was sealed in a plastic bag and immersed in an isothermal water-bath (Haake C25P Circulator with Haake Phoenix II control unit), which in turn was calibrated with a NIST-certified (National Institute of Standards and Technology) RTD (resistance temperature detector), which detects linear positive changes in resistance with temperature. The resistance was measured with a digital multimeter (HP-34401A, Hewlett Packard) set in 4-wire mode using two leads for voltage and two for current. Because the pins are relatively large, to minimize the overall size of our devices we used only two pins. The leads reach down only to the back end of the pins, thus the pin resistance and contact resistance of the pin on the metal film are part of the measurement. However, by virtue of the use of the Au-coated pins, the contact resistance was estimated to be on the order of 0.3 Ω, which is much less than the resistance of the heater (15–22 Ω) in the test temperature range. The pin contact points receive constant pressure and lie far from the heater, directly above the heatsink where the temperature remains constant (∼22 °C). We found that these conditions minimize variations of contact resistance, and it was very stable unless the pins were moved. By performing all the measurements without moving the pins, we reduced the effect of contact resistance variation to levels difficult to detect (<1%).

In a calibration run, the system first measured room temperature, and then ramped the temperature up to 80 °C in steps of 20 °C. The evaporation rate above 80 °C is not sustainable, so the instrument limits the range to this maximum. Before reading the resistance, the system allowed enough time for the temperature to stabilize at each step, approximately 30 s. At the end of the process, the system allowed the waterbath to stabilize back to room temperature before taking the final reading. We use the difference of the resistance measured at room temperature at the beginning and at the end of a calibration run as a metric of the hysteresis of the heater.

A complete calibration cycle consisted of three consecutive runs without moving the connections or taking the chips out of the waterbath. Runs #2 and #3 were carried out the day after run #1. Similarly, runs #5 and #6 were performed the day after run #4.

3.2. Joule heating

The heater chips were placed on the copper heatsink of our custom-made test instrument and clamped with a gantry carrying pogo pins that connected to the circuitry. The heatsink speeds up temperature stabilization and cooling, and is large enough to remain at room temperature over the duration of the experiments. There is a circular hole in the heatsink to which the heater is aligned. This hole provides local thermal isolation and allows the heater to reach high temperatures. Two thermocouples (STC-FF/40.36, Omega Engineering Inc.), calibrated in the waterbath, were taped onto the heatsink with adhesive pads (Omega Engineering Inc.) at opposite points next to the chip. The average of the readings of the two thermocouples was a good indicator of the room temperature.

To induce heating, a regulated current was passed through the heaters and increased in steps up to 172 mA. The resistance was calculated from the reading of a digital multimeter (DMM) measuring the applied current and a second DMM measuring the voltage at the ends of the pogo pins. The temperature along the heater ring cannot be measured directly by a contact sensor, such as a thermocouple, without altering its temperature. Instead, we chose to estimate temperature indirectly from the calibration data and measured heater resistance using:

$$T = T_m + \frac{R - R_m}{m}$$  \hspace{1cm} (1)

where $T_m$ is the room temperature measured at the beginning of the experiment (°C); $R$ is the measured resistance (Ω); $R_m$ is the room temperature resistance (Ω); and $m$ is the slope of the calibration curve of runs #3 or #6 (Ω/°C). With the relation above and the known room temperature, we corrected for variations of the reference resistance $R_m$ for the same chip across the two instruments (waterbath and Joule heating test instrument). Although the calibration curve does not cover the entire operating temperature range of the heater, we believe that the high linearity observed in the calibrated range of 20–80 °C holds at higher temperatures, at least to the point of the KMPR degradation point (200 °C [28]).

The temperature calculated from Eq. (1) yields the average temperature along the heater, including the interconnect areas, where temperature is not uniform. We found by simulation that
the average temperature of the heater is only 1.5% lower than the temperature measured in the water bath, in which the heater temperature is uniform. As an example, the resistance measured at 80 °C in the waterbath will be the resistance measured when the heater is at 78.8 °C during Joule heating. Since this error is quite small, we directly map the heater’s resistance in the water bath to the Joule-heating resistance.

To test how reproducibly the heater could reach the same resistance at a given temperature, the current through the heater was raised, held for a defined hold time, turned off, and then raised again to the previous value. A period of 30 s for heating and 3 min for cooling back to room temperature was allowed for the heater temperature to stabilize before taking a reading and counting the hold time. We verified that the heater experienced no measurable resistance change by the end of these periods. The stable voltage across the heater was then recorded.

The resistance at room temperature was measured by applying a very small current (0.33 mA), in order to produce negligible Joule heating. This current, given the $PR$ dependence of the power on the current, results in negligible power dissipation (approximately 1.7 $\mu$W). We measured that in order to increase the heater temperature by one degree from room temperature, a current approximately two orders of magnitude higher is required.

In the first Joule heating test, the current was increased gradually in intensity and time in order to avoid a thermal shock that could cause a heater fracture. The experimental sequence was as follows: (1) 0.33 mA were passed through the heater to measure $R_1$. (2) The current was raised to 123 mA, held for 30 s to allow temperature settling, and then a chronometer was started to count the hold time. The resistance $R_1$ was measured during this time. (3) After 15 min the timer was stopped, the current was turned off and the system was allowed to cool down for 3 min. (4) The current was raised again to 123 mA, but only held for 1 min in order to measure the resistance $R_2$. The difference $\Delta R = R_1 - R_2$ and its temperature counterpart (calculated from Eq. (1)) $\Delta T = T_1 - T_2$ were used as a metric of the stability of the film. This sequence was repeated with 148 mA, and 172 mA using a hold time of 30 min at each level. Finally, the sequence was repeated one more time, again at 172 mA and for 30 min, to ensure there was no additional change in $R_2$. After returning to the waterbath for the second calibration cycle, the second Joule heating test was performed. This second Joule heating test was performed in the same way as the first, but with adjustments; the current was raised to 172 mA directly, and the hold time was increased to 2 h and 3 h (from 30 min) for two consecutive tests. During these tests the heaters were monitored for fracture and other types of damage with a microscope.

We expected that the gradual increase of temperature and short hold time in the first test would bake the polymer in the heater area, resulting in a progressive increase in its glass transition temperature ($T_g$) resulting in higher hardness and mechanical stability. Reynolds et al. [28] measured the shift of $T_g$ with baking temperature and time for KMPR. From this work we estimate that the initial $T_g$ in our films is within 95–105 °C, and reaches 120–130 °C from the Joule heating tests.

4. Results and discussion

4.1. Characteristics of the Al film on KMPR

An example of the fabricated heater is displayed in Fig. 1. We found that a hard-bake of KMPR for shorter times or lower temperature (e.g. 15 min at 120 °C) leads to ridge formation on the Al film and a non-linear resistance vs. temperature characteristic, which renders the heater unusable (data not shown). The observed ridges, shown in Fig. 2, are of the labyrinth-type (described in [16,40]) and appear when baking the positive photoresist at 115 °C, which we attribute to the stresses in the system. Since the Al deposition occurs at temperatures above room temperature, an intrinsic compressive stress develops in the film upon cooling due to differential thermal expansion [41]. KMPR also expands thermally during Al deposition and will also contribute to the total stress of the system. We believe that the $T_g$ of KMPR with the aforementioned baking conditions is too low (70–80 °C, estimated from [28]), and hence the KMPR softens substantially when heated to 115 °C, to a point where the stress overcomes the mechanical strength of the polymer and corruges the metal. We observed that this corrugation/ridging is irreversible. We also found that sufficiently hard-baked KMPR was stable against these mechanical effects. If KMPR is baked at 130 °C for 30 min, polymerization advances, $T_g$ moves up to 95–105 °C, and hardness increases [42], resulting in a KMPR film that is rigid enough to withstand these stresses and maintain the Al film smoothness.

Using these settings, four heaters of 211–241 ± 12.6 nm thickness were patterned on a 50 μm hard-baked KMPR layer. After sputtering, the Al film displayed a smooth glossy appearance that was preserved across the lithography and etching processes. The metal did not crack and did not develop ridges, meaning that KMPR had reached a high degree of polymerization and structural rigidity.

The chemical resistance of KMPR after hard-baking is less than that of SU-8, however it can still tolerate acetone in microchannels for 1 h and immersion in isopropyl alcohol for 1.5 h [31]. When hard-baked at 130 °C for 30 min, KMPR survived lithography with no discernible negative effects, but we observed a degree of permeability to acetone that caused stresses and detachment from the substrate after a 30 min immersion. For shorter periods (3–5 min), the absorption of acetone in KMPR caused cracking of the Al film. For this reason we reduced exposure to acetone to the minimum (10 s) necessary to strip the HPR-504 resist. Using the tape test (described further in Section 4.5), the Al heaters showed excellent adhesion to KMPR at room temperature.

If it was necessary to pattern the KMPR floor layer, it would have to be hardbaked before aluminum deposition and patterning. Provided that the aluminum is deposited on properly hardbaked KMPR (as described in Section 2 and [25]), no effect on metal adhesion to KMPR should occur during a final KMPR development step. This concept was demonstrated in [32,33].
4.2. Resistance behavior

4.2.1. First calibration cycle and joule heating test

Before the application of any current, the heaters displayed acceptable linearity and hysteresis levels in the first calibration cycle, as illustrated in Fig. 3. However, the resistivity was clearly unstable, as the calibration curves were progressively shifting up, again clear from Fig. 3. Furthermore, the slope across all the chips showed an important deviation of $2.1 \times 10^{-2} \Omega/\circ C$, which corresponds to a measurement error in a theoretical sensor of $\pm 0.62 ^\circ C (0.38\%)$ at $164.5 ^\circ C$. This was calculated from Eq. (1) with $n_{mean} = 4.82 \times 10^{-2} \Omega/\circ C, T_{ref} = 23.30 ^\circ C, R_{ref} = 15.48 \Omega, R = 22.29 \Omega$. In these chips, contraction of KMPR was negligible, owing to the hard-bake significantly advancing the cross-linking and the water-bath temperatures being too low to produce any significant cross-linking or solvent loss in the KMPR. Therefore, the trend of the resistance to increase over calibration runs may be due to a combination of thermal strain and a small degree of recrystallization, occurring mainly at $80 ^\circ C$ [41].

The first joule heating test was aimed to determine whether the Al-KMPR system could survive temperatures above $100 ^\circ C$ for short periods of time, as is often required for LOC devices to perform fundamental operations, such as PCR.

The results of the test are summarized in Table 1. We attained heater temperatures of up to $165 ^\circ C$, corresponding to 22.3 $\Omega$ (Eq. (1)), for periods no longer than 30 min. Gardner and Flinn [41] observed that temperatures between 100 and 200 $^\circ C$ induce substantial recrystallization in sputtered Al films. Therefore, we expected that this test could anneal the film and stabilize its resistivity. The current through the heater was raised to the same level two consecutive times, with a cooling period in between, as explained in Section 3.2. The resistance and temperature were measured each time, and the mismatch $\Delta R$ and $\Delta T$ was used to evaluate the stability of the heater.

The worst stability in terms of calculated temperature $\Delta T$ was $0.74 ^\circ C$ at $86 ^\circ C$, after holding the 123 mA current for 15 min. At the highest temperature reached $165 ^\circ C$ $\Delta T$ was $0.42 ^\circ C$ after holding the current for 30 min. In both cases, the variation was less than 1%. A clear trend of $\Delta R$ and $\Delta T$ to become smaller indicated that the film was actually being annealed. Holding a current of 172 mA for 30 min seemed to stabilize the film thereafter. The maximum current density through the heater was $7.81 \text{ mA/}\mu\text{m}^2$ at steps 3 and 4 in Table 1. The best and average stability recorded across all the chips was 0.06 $^\circ C$ and 0.35 $^\circ C$, respectively. Notably, defects of up to $\sim 75 \mu m$ (caused by particles, bubbles, etc.) did not have a discernible impact on the heater’s resistance, as long as there was good coverage of metal, showing that the heaters are tolerant to defects. None of the heaters fractured with the temperature cycling and no adhesion loss was observed.

<table>
<thead>
<tr>
<th>Step</th>
<th>Hold time (min)</th>
<th>Applied current (mA)</th>
<th>Reached temperature (°C)</th>
<th>Resistance mismatch, $\Delta R$ (mΩ)</th>
<th>Temperature mismatch, $\Delta T$ (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15</td>
<td>123</td>
<td>86</td>
<td>−36</td>
<td>−0.74</td>
</tr>
<tr>
<td>2</td>
<td>30</td>
<td>147</td>
<td>121</td>
<td>31</td>
<td>0.65</td>
</tr>
<tr>
<td>3</td>
<td>30</td>
<td>172</td>
<td>166</td>
<td>20</td>
<td>0.42</td>
</tr>
<tr>
<td>4</td>
<td>30</td>
<td>172</td>
<td>165</td>
<td>20</td>
<td>0.42</td>
</tr>
</tbody>
</table>

Fig. 2. Optical images of ridges on the Al film, formed by compressive stresses on insufficiently hard-baked KMPR ($120 ^\circ C$ for 15 min). (a) Ridges on heaters caused significant hysteresis and nonlinear temperature vs. resistance curves; (b) zoomed-in image of the rectangular region in (a). Baking at $130 ^\circ C$ for 30 min raised $T_g$ sufficiently to avoid such deformations.

Fig. 3. First calibration cycle of a typical Al heater on KMPR, comprising three calibration runs in a row. The plot contains three curves that show a trend between calibration runs of increasing resistivity. Blue – run #1; green – run #2; red – run #3. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

Table 1

First joule heating results of a prototype Al heater on KMPR. At each step, the current was turned on, held for the times specified in the second column, turned off to allow the heater to reach room temperature, and finally turned on again. Resistances were measured with the applied current, and them mismatch between the two values reflects the film’s stability.
4.2.2. Second calibration cycle and Joule heating test

The heaters were calibrated again (another three-run cycle) and the curves obtained, shown in Fig. 4, revealed a highly linear, stable and hysteresis-free behavior, clearly enhanced compared to the first cycle (Fig. 3). This result suggests that resistive annealing occurred with a significant degree of recrystallization and stress-relief of Al, again since recrystallization has been observed to take place between 100 and 200 °C when the metal is strained by thermal expansion [41]. This phenomenon creates new unstrained grains and removes dislocations in aluminum crystallites caused by sputtering, thereby softening the material and decreasing stress [41]. No deformation/relief of KMPR nor ridging of Al were observed, possibly indicating that KMPR acquired higher mechanical stability by advancing polymerization in the heater area, shifting up $T_g$ to 120–130 °C (estimated from [28] for a 160 °C bake), and further increasing its hardness as reported in [42].

The surface oxide plays an important role in the film’s stability, as it prevents corrosion even at the higher temperatures reached in Joule heating. Lu et al. [43] found that further growth of the surface oxide of sputtered Al films is not significant below 250 °C, even exposed to 100 sccm of pure oxygen flow and plasma.

To analyze the evolution of the resistivity during these experiments, the calibration data in Figs. 3 and 4 were fitted to a line. The slope, intercept and $R^2$ of the fitted line of each calibration run are shown in Fig. 5. The plots again verify the important stabilization effect of resistive annealing, as the variation of these quantities decreases substantially after annealing. In Fig. 5(a), the slope standard deviation decreases from 1.2 × 10⁻⁴ Ω°C⁻¹ (runs #1–3) to 1.0 × 10⁻⁵ Ω°C⁻¹ (runs #4–6). Similarly, in Fig. 5(b) the intercept deviation decreases from 4.0 × 10⁻² to 4.6 × 10⁻³ Ω. In addition, the $R^2$ coefficient gets closer to 1. The fluctuation of these parameters in the second calibration cycle can be caused by systematic error, although the stabilization process may actually progress, since recrystallization may continue at a small rate when the waterbath reaches 80 °C [41].

The second Joule heating test was aimed to establish the feasibility of the Al-KMPR system to sustain a PCR reaction for the minimum time necessary, which can be up to 3–4 h [44]. During this length of time the resistivity needs to be highly stable as PCR temperatures must be precisely controlled for efficient and selective amplification [28]. To this end, the same maximum current was passed through but for longer hold times.

The results of the test in Table 2 show that the film’s resistivity is almost unchanged for over 5 h of sustained heating. The worst $\Delta T$ observed was 0.26 °C ($\Delta R = 13$ mΩ), after 3 h. Compared to the worst $\Delta T$ of the first experiment (0.74 °C), this was an improvement in stability of 2.8 times, and a temperature variation of less than 0.2%, which can be due to systematic error. This degree of stability is the result of resistive annealing.

After more than 6 h of total sustained heating at 140–165 °C, the duration of both the first and second tests, no change in the film’s surface uniformity was detected (see Fig. 1). Although KMPR was exposed to these temperatures that are much higher than the hard-bake (130 °C), the metal did not develop ridges. The CTE of KMPR, assuming it comparable to that of SU-8 (52–150 ppm/K [8]), is significantly higher than for Al (∼23.1 ppm/K [41]). This mismatch generates tensile stresses on the Al film. However, even after repeated heating/cooling cycles, no cracks or fractures of Al were detected. Adhesion was maintained, as confirmed by the tape test. This behavior of the Al-KMPR system suggests that the temperature
Table 2
Second Joule heating test results of a prototype Al heater on KMPR. At each step the current was turned on, held for the times specified in the second column, turned off, allowing the heater to reach room temperature, and finally turned on again. Resistances were measured with the applied current, and the mismatch between the two values reflects the film’s stability.

<table>
<thead>
<tr>
<th>Step</th>
<th>Hold time (h)</th>
<th>Applied current (mA)</th>
<th>Reached temperature (°C)</th>
<th>Resistance mismatch, ΔR (mΩ)</th>
<th>Temperature mismatch, ΔT (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>172</td>
<td>162</td>
<td>0.012</td>
<td>−0.25</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>172</td>
<td>160</td>
<td>0.013</td>
<td>0.26</td>
</tr>
</tbody>
</table>

can be increased beyond 165 °C, up to the limit of the decomposition temperature of KMPR (200 °C, which produces 5% mass loss [28]).

4.3. Resistivity and TCR

Final values for the TCR (α) and room temperature resistivity (ρ0) of the Al film were calculated using the length to cross-section area ratio L/a of the heaters and the data of calibration run #6. The L/a ratio was calculated for each heater from their individual thicknesses, ranging from 211 to 241 ± 12.6 nm. The results are shown in Table 3, along with values for other film and bulk materials for comparison. The TCR of the Al film is 75–90% of the bulk value. The resistivity is 1.6 times higher than the bulk value but still in the range reported by others on inorganic substrates [45–48]. The measured α for the Al film is of the same order as for a Pt film. In the test range the observed behavior is also as linear as for Pt. Therefore the Al film can readily replace Pt in integrated heater and temperature sensor applications.

The oxide fraction in Al films does not have a significant impact on the resistivity until it reaches a certain limit. Faith et al. [47] used the resistivity as a measure of the oxygen content in Al films, with the resistivity being insensitive to the oxygen content until about a 5% content, corresponding to O2 pressures of ~10−3 Pa (7.5 μTorr), but depending on deposition rates, sputtering distance, etc. Kubový and Janda [48] noted that at low residual gas pressures the resistivity remained approximately at 5 × 10−8 Ω-m, but showed a sharp increase when the oxide content exceeded 20%. We therefore estimate that the oxide content in our films is on the order of 5–20%, and has the effect of moderately increasing the resistivity of the film.

4.4. Resistance repeatability and measurement precision

4.4.1. Same chip repeatability

The variation of the slope of the curves in Fig. 4 was found negligible in all the chips tested. In runs #4–6, after 11 h effective test time in the waterbath, the slope changed with a standard deviation of α ≈ 7 × 10−5 Ω/°C, i.e. 0.13%, corresponding to a measurement error of ±0.2 °C at 162 °C. This is the heater temperature precision that can be ensured by performing a per-chip calibration, as estimated from Eq. (1). Table 4 summarizes the calculation by taking one of the recorded data points as a reference. We are typically concerned with temperature accuracy to within 1 °C. Therefore, in sensor applications only one calibration run after annealing is necessary to obtain parameters for highly accurate temperature measurements.

4.4.2. Chip-to-chip repeatability

The slope standard deviation after annealing, as measured from chip-to-chip, was α ≈ 1.3 × 10−3 Ω/°C, representing ±2.3% variation, corresponding to ±3.7 °C at 162 °C (see Table 5). However, the temperature is highly influenced by variations of film thickness. In other words, a change in slope may be due to variations in both thickness and resistivity. Since we measured a relatively large thickness deviation of ±12.6 nm (5.6%) across different heaters, it is better to use the TCR (α) to calculate measurement error. At the same temperature, the resistivity at each point of the wafer is different, meaning that α is also different; therefore, the deviation of α is a measure of the wafer-wide uniformity of the resistivity. The standard deviation of α was measured to be ±0.059 × 10−3 K−1 or ±1.7% (see Table 3). In a heater of standard dimensions, this produces a measurement error of about ±1.5%, corresponding to ±2.4 °C at 162 °C (see Table 6). This was calculated from:

\[ R = \frac{L}{wh} \rho_0(1 + \alpha(T - T_0)) \]  

where L, w and h are the heater length, width and thickness, respectively; \( \rho_0 \) is the resistivity at reference temperature; α is the TCR and T0 is the reference temperature (22 °C). A set of three curves was built with Eq. (2) in the range T = [22,170] °C. The slope of each curve was calculated for α and its upper and lower bounds. Then the temperature that a theoretical sensor would measure was calculated from Eq. (1), with the resistance measured at 162 °C (24.35 Ω) as a reference. Table 6 summarizes the results of the calculation.

Therefore, in a process with good thickness control, only one chip in the wafer would need to be calibrated if a maximum error of 1.5% is acceptable. The error decreases with temperature. For instance, at 100 °C, the error is calculated to be 1.3%. Therefore, in the worst-case scenario of a PCR system, the error in heater temperature Th would be about ±1.4 °C at the denaturation temperature (94 °C). In a typical PCR device, however, the temperature in the

<table>
<thead>
<tr>
<th>Slope, m (Ω/°C)</th>
<th>Temperature, T (°C)</th>
<th>Error (°C)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean + σ</td>
<td>0.05043</td>
<td>158.41</td>
<td>−3.63</td>
</tr>
<tr>
<td>Mean</td>
<td>0.04911</td>
<td>162.04</td>
<td>0</td>
</tr>
<tr>
<td>Mean − σ</td>
<td>0.04779</td>
<td>165.87</td>
<td>3.83</td>
</tr>
</tbody>
</table>

Table 3
Mean temperature coefficient of resistivity and resistivity at room temperature of Al on KMPR after annealing. Values for other film and bulk materials are shown for comparison.

<table>
<thead>
<tr>
<th>Material</th>
<th>α (× 10−4 K−1)</th>
<th>ρ0 at 22 °C (× 10−6 Ω-m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al on KMPR (this work)</td>
<td>3.52 ± 0.059</td>
<td>4.39 ± 0.16</td>
</tr>
<tr>
<td>Bulk aluminum [19,54]</td>
<td>3.90–4.71</td>
<td>2.67–2.82</td>
</tr>
<tr>
<td>Platinum thin film on SiNx, Si [27] or SiO2 [55]</td>
<td>1.96–3.30</td>
<td>15–30</td>
</tr>
<tr>
<td>Bulk platinum [19,27]</td>
<td>3.92–4.00</td>
<td>10.55–10.58</td>
</tr>
</tbody>
</table>

Table 4
Same-chip repeatability. Error in a theoretical temperature measurement due to slope uncertainty. Data from second calibration cycle is used as a reference. Eq. (1) is solved with the following parameters: \( \sigma = 7 \times 10^{-6} \, \Omega/°C, T_0 = 23.30 °C, R_0 = 15.48 \, Ω; R = 22.29 \, Ω \).
Table 6

<table>
<thead>
<tr>
<th></th>
<th>TCR, α (×10⁻³ K⁻¹)</th>
<th>Slope, m (Ω/°C)</th>
<th>Temperature, T (°C)</th>
<th>Error (°C)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean + σ</td>
<td>3.577</td>
<td>0.05836</td>
<td>159.68</td>
<td>2.32</td>
<td>1.43</td>
</tr>
<tr>
<td>Mean</td>
<td>3.518</td>
<td>0.05740</td>
<td>162.00</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Mean – σ</td>
<td>3.459</td>
<td>0.05643</td>
<td>164.40</td>
<td>2.40</td>
<td>1.48</td>
</tr>
</tbody>
</table>

PCR chamber (Tc) is a fraction of Th and therefore variations of Th attenuate at the chamber level, and hence the error in Tc will be under 1.3%.

4.4.2.1. Batch to batch repeatability. In unpatterned Al on KMPR we observed that films sputtered at Ar pressures between 7 and 11 mTorr did not develop defects, i.e. ridges or cracks, even after being annealed in an oven at 200 °C. This mechanical stability was also associated with a consistent resistivity. This property was measured at 22 °C on the unpatterned metal using a 4-point probe. We confirmed that the resistivity and deposition rate are significantly sensitive to deposition pressure. In the aforementioned pressure range, the resistivity of annealed samples at room temperature varied within ±10%. From this we estimate a worst case TCR deviation of ±6.3%. We believe that constraining the deposition pressure to 7 ± 0.5 mTorr or better, the TCR deviation can be reduced to the ±2% level, although per-wafer calibration and annealing will still be necessary for high accuracy applications.

4.5. Al-KMPR adhesion

As mentioned throughout the work in this paper, the adhesion of the Al heaters to the underlying KMPR structure is exceptionally strong. Immediately following the initial sputtering step, the blanket-deposited Al-on-KMPR passed the tape test at all tested locations of the wafer. After the first Joule heating test in which the heater was brought to 165 °C, the patterned aluminum again passed the tape test. Finally, after a total of more than 6 h at high temperature, the heater yet again passed the tape test, showing its robust adhesion to the KMPR layer underneath. Indeed, standard tape tests were performed at each step of the fabrication and testing processes, and the metal-KMPR adhesion never failed. This level of metal adhesion is not observed on other polymer materials. In fact, it is often very difficult to achieve even moderate adhesion [49–51]. Adhesion between other metals and polymers often fails at room temperature, let alone at the high temperatures required for PCR, where thermal mismatch causes high stresses. Our process did not require any chemical adhesion promoters, surface treatments (such as O₂ plasma) or additional adhesion layers such as Cr or Ti. Furthermore, over time, adhesion has been maintained – our older samples still pass the tape test 12-months after patterning.

To qualitatively demonstrate the exceptional adhesion of aluminum on KMPR in comparison to other commonly used LOC polymers, an additional tape test on various substrate materials was done. Al was deposited as described in Section 2.2 onto substrates of PMMA, polycarbonate (PC), SU-8 on Si and KMPR on Si. All substrates were processed the same way, with no adhesion promotion or surface treatment of any kind. The PMMA and PC substrates were cleaned gently with water and IPA to remove contaminant oils and dust prior to Al sputter-deposition. Both the SU-8 and KMPR
were spun to a thickness of 20 μm, pre-baked for 10 min at 100 °C, and blanket-exposed with a dose of 1 J/cm². The SU-8 on Si was post-baked for 30 min at 100 °C and the KMPR for 60 min at 150 °C. Aluminum was sputter-deposited to a thickness of 200 nm, and all four substrates were in the chamber together, so as to ensure identical films.

“Crystal Clear Tape” (Grand & Toy, product code 99110) was used for the tests. This product has aggressive adhesion, even stronger than that of typical packing tape. Fig. 6 clearly displays the key result of the test; the aluminum was easily and completely removed from the PC, PMMA and SU-8 substrates, yet maintained excellent adhesion to KMPR.

While this test lacks rigorous quantitative values, it shows the significant difference in adhesion strength of aluminum deposited on KMPR compared to other common LOC substrate materials. Since the patterned metal exhibited such strong adhesion compared to results typical of metallization on other polymers, quantification of the adhesion strength should be explored. Such quantification does not have a significant impact on the focus of this particular work, however, and as such will be relegated to future publications.

### 4.6. Electromigration effects

For pure Al connected to DC power, a conservative electromigration limit is 1–2 mA/μm² for conductors at 110 °C [36]. In our experiments, this limit was greatly exceeded (7.8 mA/μm², 165 °C). We expected that these conditions would cause severe electromigration and heater failure in a short time. Contrary to our expectations, the heaters survived all the experiments (~6h) with no apparent damage. Closer inspection revealed electromigration-induced hillocks, with highest incidence and largest size at the interconnections of the heater ring to the contact pads. We found by simulation (see Fig. 7) that these are the areas of maximum combined current density and temperature, which supports the electromigration origin of the hillocks.

![Optical images of Al heaters on KMPR](image)

**Fig. 8.** Optical images of Al heaters on KMPR. The size and density of hillocks due to electromigration increase with operation time. (a and d) Film before application of current; (b and e) film after 1 h of ~165 °C Joule heating; (c and f) film after 6 h of ~160 °C Joule heating. Deliberate shallow scratches to the film (d–f) confirmed that hillocks proliferate on defects.
In our work, electromigration progressed at a low rate along the experiments, as shown in Fig. 8, without creating voids. Electromigration did not have a measurable effect on the resistance characteristics of the heaters. We believe that the addition of oxides to the film increased its resistance to electromigration, giving an effect similar to doping Al with Cu. Al–Cu alloys, however, are susceptible to corrosion [34,38], and thus their properties are at risk of changing when exposed to oxygen and other corrosives. The Al-Al2O3 heaters of this work are not, however, susceptible to corrosion due to the highly stable surface passivation oxide of the film. The increase in electromigration resistance may be caused by the oxide crystallites in the film creating stress fields that oppose the transport of Al.

Interestingly, this effect of oxides is quite in contrast to reports in the literature. Reicha et al. [52] noted that oxygen contamination leads to the formation of hillocks during deposition (distinct from the aforementioned electromigration hillocks), and Reimer [53] observed that more oxygen-induced hillocks appear at higher pressures. Reimer also noted that electromigration effects were strongly affected by oxygen (and other contaminants), with an electromigration failure rate that increases with contaminant pressure, and that is approximately linear for oxygen. The oxygen partial pressure of our base pressure is lower than the range of oxygen tested by Reimer and we surmise that with a low enough oxygen content the oxide may serve to hinder electromigration, while at higher concentrations the higher resistivity and current density caused by the presence of the oxide actually stimulate the electromigration (as seen by Reimer). Whatever the source of this stabilization against electromigration, it is certainly useful and warrants further study.

We noticed that hillocks tended to populate defects, and verified this in an independent experiment. Scratches of few nanometers depth were produced on a heater by rubbing a cotton tip wet in isopropl alcohol. Subjected to the same experimental procedure, the heater formed hillocks preferentially at defect locations over time (see Fig. 8d–f), but again, the stability of the heater’s resistance was not affected by hillocks and scratches. Metal coverage in defects is poor, and hence current density and Joule heating increase and accelerate electromigration and hillock formation.

4.7. Resistive vs. batch annealing

The annealing of the metal film was accomplished via resistive Joule heating, as described. It should be noted, however, that annealing could have been accomplished by oven-heating the entire device. Such batch-annealing is cost effective and simple, but per-device resistive annealing offered significant advantages. Firstly, annealing and calibrating devices in one step yields information about how the stability of the microfabricated heaters changes. Furthermore, in applications where a heater must be fabricated with other, more temperature-sensitive layers or processes, a batch-annealing process may not be possible. The resistive annealing method is selective in its heating, allowing for a wider range of fabrication possibilities. For example, membranes and cantilever MEMS structures often depend on careful thermal stress management, and may be adversely affected by a batch anneal step.

In considering the purposes of this research, the resistive annealing method was more desirable.

5. Conclusions

We presented a method to produce a stable non-metal film that can be patterned by standard lithography on a photopolymer and then stabilized through resistive annealing. The film has a sufficiently high resistivity and TCR for use as a heater or temperature sensor. We demonstrated that the film is mechanically and electrically stable in contact with air for at least 6 h at ~160 °C and 7.8 mA/μm² current density.

The stability shown at temperatures greater than 100 °C makes the film suitable for use as a heater or sensor in disposable PCR LOC systems. In sensor applications, a temperature measurement error of ±0.13% can be performed by per-chip performance, since the slope of the resistance vs. temperature curve of a typical heater varies by 7 × 10⁻⁵ °C⁻¹. If only one chip per wafer is calibrated, the error will be within ±1.5%, since the TCR of all the chips in the wafer varies by 59 × 10⁻⁶ K. In a PCR system, the error at the chamber level will be smaller since the chamber temperature is a fraction of the heater temperature, and hence variations attenuate.

In this work, the addition of oxides to the Al film provides resistivity above the bulk value, and is thought to increase its resistance to electromigration. In contrast to the effects of Cu in a Cu–Al alloy, the oxides likely protect the film from corrosion, even at high temperatures. The film showed adequate surface uniformity and strong adhesion to the photopolymer, without any additional adhesion layers or other treatments. This is an important point, since avoiding additional adhesion layers or chemical promoters simplifies the fabrication process and reduces time and cost significantly. Finally, and perhaps most significantly, the fabrication process and materials are compatible with CMOS technology, enabling the possibility of true integration of electronic infrastructure and microfluidics. To the best of our knowledge, this is the first demonstration of a stable, non-metal thin film heater/sensor fabricated on a photopatternable polymer in the LOC field.

This work builds on our previous demonstrations of a multilayer bonding method for complex KMPR structures [39] and a characterization of KMPR structural properties [28]. Moving forward with the results reported here, we will demonstrate a novel approach for designing power density-controlled aluminum heaters on KMPR, and then fabricate these heaters to show robust thermal control of KMPR-aluminum-based genetic analysis systems.

Acknowledgements

We gratefully acknowledge the support of Alberta Innovates Technology Futures, the Natural Sciences and Engineering Research Council of Canada and Teledyne-DALSA Semiconductor, as well as the University of Alberta NanoFab facility.

References


Biographies

Jose Martínez-Quijada obtained the Licentiate degree in Electronics and Communications Engineering in 1998 at Universidad Bicentennaria, Mexico City. Two years later he received his Masters degree in Electrical and Computer Engineering at the University of Windsor, Canada. In 2009 he received the ICORE Graduate Scholarship, awarded by Alberta Innovates Technology Futures, and currently he is a PhD candidate in Electrical and Computer Engineering at University of Alberta, Canada. His research includes the development of medical implants and lab-on-chip systems for diagnostic applications.

Saul Caverhill-Godkwitsch received his BSc in Electrical Engineering (Biomedical) at the University of Alberta, Edmonton, Canada. In 2010 he is a student member of the IEEE, from whom he received the IEEE Life Member Award for his undergraduate Capstone project paper. Saul is currently working toward the MSc in Electrical and Computer Engineering at the University of Alberta in the field of lab-on-chip technology, and has twice received the Queen Elizabeth II Graduate Scholarship in support of these studies.

Matthew Reynolds obtained his BSc in Engineering Physics from the University of Alberta and is currently working towards his MSc in Electrical Engineering at the University of Alberta focusing on the development and fabrication of polymer-based MEMS and microfluidic devices.

Luis Gutierrez-Rivera received his BS in physics from Faculty of Science of the National University of Engineering-UNI, Lima, Perú in 2001 and his MSc and PhD in 2004.
degrees in Physics from the University of Campinas, Sao Paulo, Brazil in 2004 and 2009, respectively. Since 2010 he has been a postdoctoral researcher with the National Institute for Nanotechnology NINT and the Department of Electrical Engineering at the University of Alberta. His current interest is design, fabrication and characterization of quantum devices for Nano-biotechnology. Micro and nanofabrication specialist.

**Robert W. Johnstone** received his B.Eng. & Soc. for Engineering Physics from McMaster University in Hamilton, Canada in 1999. He received his M.A.Sc from Simon Fraser University in Burnaby, Canada, in 2001, and received his Ph.D. from Simon Fraser University in 2008. Both graduate degrees were for work in micromachining. Currently, he has published 39 conference and journal publications. Also, he has published one book, titled “An Introduction to Surface-micromachining.” Dr. Johnstone is a member of the IEEE, and a founding partner in BRG Industries.

**Duncan Elliott** is a Professor in the Department of Electrical and Computer Engineering at the University of Alberta, Edmonton, Canada. He received his B.A.Sc. in Engineering Science and his masters and doctorate degrees in Electrical and Computer Engineering from the University of Toronto. His research interests include CMOS circuit design and merged microfluidic-microelectronic systems with applications in manipulating and detecting DNA.

**Dan Sameoto** is an Assistant Professor in Mechanical Engineering at the University of Alberta specializing in polymer micromachining technologies and devices. He received his B.Eng. and M.A.Sc in Mechanical Engineering from Dalhousie University in 2002 and 2004 respectively, and his Ph.D. in Engineering Science at Simon Fraser University in 2008 where he developed a polymer based MEMS prototyping technology as part of his doctoral research. Since joining the University of Alberta he has been focused on developing biomimetic dry adhesives, smart materials, and low-cost Lab-on-Chip devices.

**Backhouse** joined the Department of Electrical and Computer Engineering at the UofWaterloo in 2011. He was at the UofAlberta from 1999-2011 coming from industry. He has a broad background in microfabrication, quantum and lab-on-chip devices, both commercial and academic. Past commercial projects involved microchip-based CE, DNA sequencing, PCR, DNA fragment analysis, cell manipulation, electrochemical detection and environmental sensing. Dr. Backhouse has developed an expertise in porting molecular biology to microfabricated devices with work published in the leading journals of the field.