1. Introduction

In recent decades, the development of microelectromechanical systems (MEMS) has been largely based on silicon as the substrate and structural material. Silicon-based sensors and actuators play a significant role in many applications, but are generally limited to electronic device applications operating under 250 °C. Furthermore, silicon MEMS devices usually require bulk packaging and are cost and space demanding [1]. On the other hand, the demand of MEMS-based sensors working under hostile conditions is growing. For instance, hazardous gas sensing requires a microfabricated sensor made of a material with low power consumption. In addition to stable operation, the sensor should quickly respond to gas leakage. A microheater can meet this requirement. Microheaters operate on the principle of Joule heating and consists of a resistive heater that is thermally isolated from the substrate. A microheater should ideally have a low power consumption and a homogenous temperature over the active area to ensure consistent sensing properties. Factors that determine the suitability of the heater material for high-temperature applications are excellent mechanical and thermal stability.

Microheaters have been fabricated using metal conductors. For instance, platinum [2] has been widely investigated, because of its thermal stability and excellent reliability. A large number of papers reported on the design and optimization of platinum-based microheaters for applications such as hand-held gas monitors [3], gas sensing for automobiles [4], and portable gas-sensing devices [5]. However, a platinum heater is easily destroyed at high current input [6]. Platinum is usually accompanied by a thin adhesive layer of titanium. The diffusion rate of this adhesive layer is high at increasing temperatures of 550 °C, which decays the platinum heater.
Other metals such as aluminium suffer from electro-migration at high temperatures [7]. Among the semiconductor heaters, polysilicon has been widely investigated in [8, 9]. However, the resistance of polysilicon is not very stable as the operating condition approaches the recrystallization temperature of 600 °C.

Consequently, an alternative to metals as a heater material is needed. Among the various wide bandgap materials, silicon carbide (SiC) possess a relatively large band gap of 2.3–3.4 eV [10] and has been available as device material for more than 100 years and can be formed in amorphous, single-crystalline, and polycrystalline solid forms [11]. Compared to Si, SiC exists in polymorphic structures called polytypes. Over 250 polytypes have been identified to date. Among the various polytypes, 3C–SiC, 4H–SiC, and 6H–SiC are the commonly employed structures [12]. Of these, 3C–SiC is the most suitable polytype for MEMS sensors, due to the SiC/Si heterojunction for providing the electrical insulation. Moreover, 3C–SiC can be heteroepitaxially grown on a silicon substrate, making it a suitable choice among their counterparts [13]. With superior physical properties [14], excellent mechanical strength, and its chemically inert nature to corrosive environments [15], 3C–SiC could be a prime candidate for microheater device material.

Recent studies on SiC microheater technology [16–19] demonstrated the potential use of SiC for high-temperature applications, especially as a key component of gas sensors. For instance, Solzbacher et al proposed a modular system of microhotplates with SiC as the membrane material and hafnium diboride as heater material. As the thermal conductivity of SiC is about three times higher than that of silicon, a suspended membrane needs to be employed to reduce the heat. Due to the excellent mechanical and chemical stability, the proposed microhotplate could well be applied for gas sensing [20]. Moreover, Solzbacher et al developed a nitrogen dioxide gas sensor by depositing indium oxide on top of an interdigitated capacitor structure [20] for stability analysis over a long period [21].

Ghosh et al developed a SiC-based microheater for detecting hydrogen-containing species in highly corrosive and radioactive environments. In fact, this sensor has shown a fast thermal response time of one millisecond [22]. On the other hand, Spannhake et al used β-SiC membrane instead of an insulating membrane. The β-SiC membrane enables long-term stability, fast response time, and low power consumption [23].

Another important application of SiC is thermal sensing in a harsh environment. Phan et al investigated the piezoresistive properties of 3C–SiC thin-film heater bridges. In this work, the 3C–SiC piezo-resistors are heated using the Joule-heating effect. The observed high temperature coefficient of resistance (TCR) proved the possibility of using 3C–SiC heaters as thermal sensors [24]. Recently, Trochimczyk et al investigated the robust performance of a 3C–SiC microheater on catalytic gas-sensing application. With the addition of a catalytic material, platinum nanoparticle-loaded boron nitride aerogel, propane gas was detected with high sensitivity.

With the advantage of combining electrical, mechanical, and thermal properties, multi-layer microheater devices have attracted attention in application areas such as the automotive, nuclear, and chemical industries [25]. Elucidating the temperature distribution and heat flow [26] inside the multiple material layers is of great interest to device developers. Owing to their importance, significant advances have been made in numerical modelling of single-layer 3C–SiC heater devices. The finite element method has been reported in [24, 27–29]. Although most industrial problems in steady-state heat conduction are solved using approximate numerical techniques, an exact solution is needed, particularly for multi-layer microheater devices.

Analytical methods such as the integral transform method [30], Laplace transform method [31], Green’s function method [32], modified Green’s function method [33], orthogonal expansion technique [34], and frequency regression method, etc, have been reported in the literature for various kinds of single-layered, multi-layered structures. However, these methods have provided only a formal solution and failed to provide an explicit solution in a classical sense. To date, there has been no steady-state analytical model developed for a multi-layer micro-heater by depositing indium oxide on top of a conducting segment of the bridge. Next, the general temperature distribution solution using Fourier’s law was obtained. This temperature distribution further allows for the determination of the voltage and power characteristics of the bridge. Furthermore, the paper also presents the detailed fabrication process and experimental verification of the proposed analytical model for three different bridge configurations.
2. Mathematical model development

Considering a two-layer and multi-segment resistive bridge suspended at both ends on the silicon substrate, is shown in figure 1(a). The total length of the bridge is 2l, varying from −l to + l. The length of the 3C–SiC-based heater element is 2l0 varying from −l0 to + l0. Let \( \kappa_1 \) and \( \kappa_2 \) represent the temperature-independent thermal conductivity of 3C–SiC and Al, respectively.

The thermal conductivity of the two-layer conducting segment is the equivalent thermal conductivity of both 3C–SiC and Al denoted by \( \kappa_e \). In addition, the electrical resistivity of 3C–SiC and Al is denoted as \( \rho_e \). The specific resistance \( \rho \) varies linearly with respect to temperature and is represented by \( \rho = \rho_0 [1 + \xi (\theta - \theta_0)] \), where \( \xi \) is the TCR. The two-layer conducting segment can be considered as a parallel circuit for the determination of the values of \( \kappa_e \) and \( \rho_e \) by electrical and thermal analogies. Figure 1(b) shows the two-layer SiC/Al conducting segment. Figure 1(c) depicts the equivalent thermal circuit. The notations used in the following model are summarized as follows. \( R \) is the equivalent electrical resistance of the parallel circuit, \( R_2 = R_{AI} \) is the electrical resistance of the Al layer, \( R_1 = R_{3C-SiC} \) is the electrical resistance of the cubic-SiC layer, \( R_{th} \) is the equivalent thermal resistance of the parallel circuit, \( A_{Al} \) is the cross-sectional area of the Al layer, \( A_{3C-SiC} \) is the cross-sectional area of the cubic-SiC layer, \( A_c \) is the total cross-sectional area, and \( l_c \) is the total effective length.

For heat conduction, the energy equation or the rate equation is known as Fourier’s law. The rate equation for the 1D solid medium composed of two segments having a temperature distribution \( \theta(x) \) is expressed as

\[
q_1 = -\kappa A_1 \frac{\Delta \theta}{l_1} = -\frac{\Delta \theta}{R_{th}},
\]

where \( q_1 \) represents the heat rate by conduction in watts and the term \( R_{th} = \frac{l}{\kappa A_1} \) represents the thermal resistance. The thermal resistance is analogous to the electrical resistance defined by Ohm’s law. Equation (1) indicates that the conduction heat rate is inversely proportional to the thermal resistance and the temperature gradient is the same across the parallel circuit. Therefore, the effective equivalent resistance of the parallel combination is given by

\[
\frac{1}{R_{th}} = \frac{1}{R_{Al}} + \frac{1}{R_{3C-SiC}}.
\]

Substituting the value of \( R \) for each layer in equation (2), we get

\[
\frac{\kappa A_c}{l_c} = \frac{\kappa_{Al} A_{Al}}{l_{Al}} + \frac{\kappa_{3C-SiC} A_{3C-SiC}}{l_{3C-SiC}}.
\]

Let \( l_{Al} = h_{BC-SiC} = l_1 = l, A_{Al} = w H_1 \) and \( A_{3C-SiC} = w H_2 \). The total area is given by \( A_c = w H_1 + w H_2 \). Substituting the geometrical terms in equation (3) leads to

\[
\kappa_e = \frac{(\kappa_{Al} H_1 + \kappa_{3C-SiC} H_2)}{(H_1 + H_2)}.
\]

Equation (4) clearly suggests that the equivalent thermal conductivity is directly dependent on the thickness of the materials. The relationship between electrical resistance and specific resistivity is represented by

\[
R = \frac{\rho}{A} = \frac{\rho}{w H}.
\]

Substituting equation (5) in equation (2) leads to

\[
R_{th} = \left( \frac{R_{H1} + R_{H2}}{\rho_{H1} + \rho_{H2}} \right).
\]

The reported specific resistance of cubic SiC of \( \rho_{3C-SiC} = 0.14 \Omega \cdot \text{cm} \) was taken for the calculations [35]. The specific resistance of aluminium, the thermal conductivity of aluminium, and the thermal conductivity of cubic SiC used for the analytical model are \( \rho_{Al} = 2.65 \times 10^{-8} \Omega \cdot \text{m}, \kappa_{Al} = 205 \text{ W m}^{-1} \text{K}^{-1}, \) and \( \kappa_{3C-SiC} = 360 \text{ W m}^{-1} \text{K}^{-1}, \) respectively. The thickness of the 3C–SiC and Al layers are 280 and 80nm, respectively. According to equations (4) and (6), the equivalent thermal conductivity and equivalent specific resistivity of the conducting segment is 326 W m⁻¹ K⁻¹ and 1.19 \times 10⁻⁸ Ω m, respectively.

The phenomenon of Joule heating occurs when an electric current is passed through the bridge, developing a temperature distribution along its length \( \theta(x) \). The maximum temperature \( \theta_{max}(x = 0) \) is found at the centre of the bridge. Assuming that free convection and surrounding radiation are negligible, the governing heat conduction equation, along with the boundary and interface continuity conditions, are as follows:

\[
\frac{\partial^2 \theta}{\partial x^2} = -J_1 \rho_1 [1 + \xi_1 (\theta_1 - \theta_0)], \quad 0 < |x| < l_0
\]

\[
\frac{\partial^2 \theta}{\partial x^2} = -J_2 \rho_2 [1 + \xi_2 (\theta_2 - \theta_0)], \quad l_0 < |x| < l
\]

where \( J_1 \) and \( J_2 \) represent the current density along the heating and conduction segments and \( \xi_1 \) and \( \xi_2 \) denote the TCR. In order to find a solution to the described problem, a set of boundary and continuity conditions need to be prescribed.

The symmetry condition at the centre is:

\[
\frac{\partial \theta}{\partial x} = 0 \text{ at } x = 0.
\]

The conditions at the ends of the bridge are:

\[
\theta_1 = \theta_x = \theta_0
\]

where \( \theta \) is the ambient temperature. The interface continuity conditions are:

\[
\theta_1(l_0) = \theta_2(l_0) \quad \text{and} \quad \theta_1(-l_0) = \theta_2(-l_0)
\]

where the segments 1 and 2 have the common temperature at their interface \( x = \pm l_0 \) as a result of the assumption of zero contact resistance.

\[
\kappa_1 \frac{\partial \theta_1}{\partial x}(l_0) = \kappa_e \frac{\partial \theta_2}{\partial x}(l_0) \quad \text{and} \quad \kappa_1 \frac{\partial \theta_1}{\partial x}(-l_0) = \kappa_e \frac{\partial \theta_2}{\partial x}(-l_0)
\]
where the segments 1 and 2 have the common heat flux at their interface \(x = \pm l_0\). The position, geometrical length, and temperature difference can be non-dimensionalized to make the model more convenient as follows: \(x^* = \frac{x}{l_0}, \alpha = \frac{\theta}{\theta_0}\) and \(\Delta\theta = \theta - \theta_0\).

Using the above conventions, the governing equations (7) and (8), and the necessary boundary and continuity conditions are written in semi-dimensional form as follows:

\[
\frac{\kappa_1}{l^2} \frac{\partial^2 \theta_1}{\partial x^*} = -J_1^2 \rho_{1,0} \left[1 + \xi_{1}(\theta_1 - \theta_0)\right], \quad 0 < |x^*| < \alpha
\]  

(13)

\[
\frac{\kappa_2}{l^2} \frac{\partial^2 \theta_2}{\partial x^*} = -J_2^2 \rho_{2,0} \left[1 + \xi_{2}(\theta_2 - \theta_0)\right], \quad \alpha < |x^*| < 1
\]  

(14)

\[
\frac{\partial \theta_1}{\partial x^*} = 0 \text{ at } x^* = 0
\]  

(15)

\[
\theta_{1} = \theta_{1+1} = \theta_i
\]  

(16)

\[
\theta_{1}(\alpha) = \theta_{2}(\alpha) \quad \text{and} \quad \theta_{1}(-\alpha) = \theta_{2}(-\alpha)
\]  

(17)

\[
\kappa_i \frac{\partial \theta_i}{\partial x^*}(x^* = \pm \alpha) = \kappa_i \frac{\partial \theta_i}{\partial x^*}(x^* = 0)
\]  

(18)

Equations (13) and (14) represent a system of second-order linear ordinary differential equations. The auxiliary solution yields the complex and imaginary roots of the equations. The complete solution of the equations is represented by

\[
\theta_1(x^*) = (A \cos \gamma_1 x^* + B \sin \gamma_1 x^*) + \left(\theta_0 - \frac{1}{\xi_1}\right), \quad 0 < |x^*| < \alpha
\]  

(19)

\[
\theta_2(x^*) = (C \cos \gamma_2 x^* + D \sin \gamma_2 x^*) + \left(\theta_0 - \frac{1}{\xi_2}\right), \quad \alpha < |x^*| < 1
\]  

(20)

where \(A, B, C, D\) and \(\gamma_1 = J_1 \sqrt{\frac{\kappa_1}{\rho_{1,0}}}, \quad \gamma_2 = J_2 \sqrt{\frac{\kappa_2}{\rho_{2,0}}}\). The constants are represented as:

\[
A = \frac{J_1}{\xi_1} + \left(\frac{1}{\xi_2} - \frac{1}{\xi_1}\right) \cos \gamma_2(\alpha - 1) / \cos \gamma_1 \cos \gamma_2(\alpha - 1) + \left(\frac{\gamma_1}{\kappa_1 \xi_2}\right) \sin \gamma_1 \sin \gamma_2(\alpha - 1)
\]  

(21)

\[
B = 0
\]  

(22)

Applying symmetry condition (15) to equation (19) leads to \(B = 0\) and applying the boundary condition to equation (20) results in

\[
C \cos \gamma_2 + D \sin \gamma_2 = \frac{1}{\xi_2}
\]  

(25)

Applying the continuity condition to equations (19) and (20) results in

\[
A \cos \gamma_1 \alpha - C \cos \gamma_2 \alpha - D \sin \gamma_2 \alpha = \frac{1}{\xi_1} - \frac{1}{\xi_2}
\]  

(26)

Applying the interface heat flux condition to the differential forms of equations (20) and (21) leads to

\[
A \left(-\frac{\kappa_1}{\kappa_2}\right) \sin \gamma_1 \alpha + C \sin \gamma_2 \alpha - D \cos \gamma_2 \alpha = 0
\]  

(27)

Equations (25)–(27) represent a system of three linear equations and three constants. The constants were obtained by Cramer’s rule (21)–(24). The constants were obtained for the boundary and continuity conditions in the range of \(0 < |x^*| < 1\). The constants for the range of \(0 < |x^*| < 1\) are symmetric with respect to \(0 < |x^*| < 1\). The constants \(A, C, D\) depend on the geometrical length ratio, thermal conductivity of two segments, thickness, width, and electrical resistivity of the segments. Furthermore, the temperature distribution along the bridge is directly dependent on the applied current \(I\) and the geometry of the segments. Using equation (16), the maximum temperature at the centre of the bridge could be determined as:

\[
\theta_{\text{max}}(x^*) = \left[\frac{\frac{1}{\xi_2} + \left(\frac{1}{\xi_2} - \frac{1}{\xi_1}\right) \cos \gamma_2(\alpha - 1)}{\cos \gamma_1 \cos \gamma_2(\alpha - 1) + \left(\frac{\gamma_1}{\kappa_1 \xi_2}\right) \sin \gamma_1 \sin \gamma_2(\alpha - 1)}\right] + \left(\theta_0 - \frac{1}{\xi_1}\right)
\]  

(28)

The voltage between \(x = 0\) and \(x = l_0\) is the difference in electrical potentials between these two points:

\[
V(l_0) - V(0) = -\int_0^{l_0} E \cdot dx.
\]  

(29)

As the mediums possess non-zero resistance, the electric field \(E\) and the electrical conductivity \(\sigma\) are related by \(J = \sigma E = \frac{E}{\rho}\).
was supplied. A...was used as a p-type dopant for the preparation of...\]

\[Jx\]

was measured to be naturally p-type conductivity [38].

This relationship is an analogous form of Ohm’s law, stating \( V = IR \). Equation (29) can be written in terms of current density and electrical resistivity as follows:

\[
V(0) - V(\alpha) = -\int_0^\alpha \rho J_1 \cdot dx.
\] (30)

The voltage as a function of current can be determined with the temperature solutions obtained in equations (19) and (20), and equation (30) can be non-dimensionalized as follows:

\[
V(\alpha) - V(0) = -\int_0^\alpha \rho J_1 \cdot dx^* = -J_1 \int_0^\alpha \rho J_0 \left[ 1 + \xi \left( \theta_1 - \theta_0 \right) \right] dx^*.
\] (31)

Integrating and simplifying the above equation leads to:

\[
V(\alpha) - V(0) = -J_1 \rho J_0,0 \left\{ \alpha - (\xi \theta_0,0 + \xi \left( \theta_0 - \frac{1}{\xi} \right)) \right\} + \xi \sin \gamma_\alpha \left\{ \frac{1}{\xi} + \left( \frac{1}{\xi} - \frac{1}{\xi} \right) \cos \gamma_\alpha (\alpha - 1) + \left( \frac{\alpha}{\sin \gamma_\alpha} \right) \sin \gamma_\alpha \sin \gamma_\alpha (\alpha - 1) \right\}.
\] (32)

Similarly, the voltage difference between the two points \( I_0 \) and \( I \) in the conducting segment can be obtained as follows:

\[
V(1) - V(\alpha) = \left[ 1 + \xi (\theta_0 - \frac{1}{\xi}) - (\xi \theta_0,0 + \xi \left( \theta_1 - \theta_0,0 \right)) \right] \cos \gamma_\alpha (\alpha - 1) + \left( \frac{\alpha}{\sin \gamma_\alpha} \right) \sin \gamma_\alpha \sin \gamma_\alpha (\alpha - 1).
\] (33)

The \( V-I \) characteristics of the entire bridge of length \( 2I \) is obtained as

\[
V(1) - V(-1) = 2 \{ [V(1) - V(\alpha)] - [V(\alpha) - V(0)] \}.
\] (34)

From equation (34), the power dissipated in the bridge can be determined as

\[
P = [V(1) - V(-1)] I.
\] (35)

3. Device fabrication

Microheaters are commonly designed as free released structures from the substrate in order to assure thermal isolation. Figure 2 depicts the fabrication process of 3C–SiC resistive heaters involving seven steps. Initially, 280nm thick 3C–SiC films were heteroepitaxially grown on a Si substrate of thickness 150 nm at 1273.15 K, as shown in figure 2(a). The growth process is performed in a hot-wall low-pressure chemical vapour deposition reactor by using an alternating supply epitaxy method [24] using silane (SiH\(_4\)) and propylene (C\(_3\)H\(_6\)) as silicon- and carbon-containing sources. Silicon atoms were adsorbed on the SiC surface in a self-assembled pattern when SiH\(_4\) was supplied. In addition, trimethylaluminium (TMAI) [\( (\text{CH}_3)_3\text{Al} \)] was used as a p-type dopant for the preparation of the SiC wafer. When TMAI was introduced, Al(CH\(_3\))\(_3\) bonds broke below 528 °C and Al atoms were then adsorbed on the Si-terminated surface [36]. Finally, the adsorbed Si and Al atoms formed the SiC layers when (C\(_3\)H\(_6\)) was supplied. A conventional low-pressure chemical vapour deposition reactor was used for the growth of 3C–SiC on Si substrate as it enables commercially viable SiC deposition [37]. The 3C–SiC films were characterized by a hot-probe technique and the polarity was measured to be naturally p-type conductivity [38].

The growth process was followed by coating the PR by a photolithographic process, as shown in figure 2(b). First, the PR was coated and then SiC resistors of dimensions 12 × 8 \( \mu \)m were patterned (not to scale) using a mask, as shown in figures 2(b) and (c), respectively. Using HCl and O\(_2\) active gases, the SiC layer was patterned, figure 2(d), and a 300nm thin aluminum layer was deposited, figure 2(e). Next, the deposited Al layer was etched to form the conducting segments of the SiC resistors, as shown in figure 2(f).

Finally, SiC resistors and Al electrodes were suspended from the SiC substrate by xenon difluoride (XeF\(_2\)) gas using a pulse etching system, as shown in figure 2(g). This method minimizes the adhesion between the SiC layer and the Si substrate due to the dry gaseous characteristics of xenon.
using have been considered for characterization 0K. This clearly. It can be clearly seen that for a current of $l$ is the. When this current is applied to the scale as infra-red (IR) wavelengths, the measurement microbridge can be plotted in figure 3(b). Using this measured data, the temperature distribution along the TCR is found to be (a) Thermoresistive effect as reported by Phan et al [24, 35], and (b) thermal profile of various SiC microbridges.

diffuoride. The overall chemical reaction involving $\text{XeF}_2 - \text{Si}$ is given by [39]

$$2\text{XeF}_2 + \text{Si} \rightarrow 2\text{Xe} + \text{SiF}_4.$$  

(36)

Figure 2(h) shows the SEM image of the fabricated SiC structures on a Si strip. A SiC microbridge with Al electrodes deposited and patterned on its top surface were suspended from the substrate, while its two ends were fixed to the substrate by fixed pads.

4. Results and discussions

Phan et al investigated the thermoresistive characteristics of the cubic 3C–SiC films, as shown in figure 3(a). The SiC structures behave like a negative temperature coefficient (NTC) resistor when the resistance decreases with increasing temperature.

The experimental data were fitted by a third-order polynomial function at low temperatures of 300–350 K and the value of the TCR is found to be $\xi = \frac{\Delta R}{R_0 \Delta T} \approx -5.2 \times 10^{-3} \text{K}^{-1}$. From this measured data, the temperature distribution along the microbridge can be plotted in figure 3(b).

As the size of the microheaters is almost on the same scale as infra-red (IR) wavelengths, the measurement of temperature using IR thermography is not feasible. Figure 3(b) shows the temperature distribution on the microbridge for three different bridge configurations $\alpha = \frac{l}{w}$ with a current of $2.92 \times 10^{-5} \text{A}$. When this current is applied to the Al/SiC conduction segment, Ohmic heating occurs and the SiC layer becomes hot and the conducting segments remain cold until the equilibrium state is achieved. Once this state was achieved, the spatial temperature gradient along the bridge remained unchanged. In other words, temperature at the anchor of the bridge is close to room temperature, with the temperature increasing farther away from this point. The temperature at the centre of the bridge, $\theta_{\text{max}} = \theta_0$ is the highest. It is to be noted that the curves were generated for the low-temperature ranges ($\approx 298 \text{ K} - 311 \text{ K}$) using $\xi_\alpha$.

Furthermore, the temperature distribution across the SiC heating segment is parabolic and remains almost linear across the conduction segments. Longer bridges exhibit higher temperature at the centre than shorter bridges. In other words, the lower the $\alpha$ value, the higher is $\theta_{\text{max}}(\alpha)$. This clearly shows the relationship between the geometry of the device and the temperature characteristics. The temperature solution obtained using normal forms of equations (20) and (21) allows us to further determine the electrical characteristics of the microbridges.

Electric measurements were performed under standard room conditions. The released SiC test structure is positioned on top of a hot plate (RT String, Thermo Scientific) using two clamps. The electrical connections from the strip to an HP 4145B analyser were established with two probe tips pushed against the aluminium electrodes on both ends. Voltage versus current ($V-\text{I}$) characteristics in air are shown in figure 4(a) for three geometrical length ratios $\alpha$ and were not normalized. Three different microbridge configurations of $l \times l_0 \times w_1 = 100 \times 10 \times 10$, $200 \times 10 \times 10$, and $500 \times 20 \times 5 \mu\text{m}$ have been considered for characterization and modelling.

As the applied current increases, the differential resistance monotonically decreases, because of the NTC of resistivity and the behaviour is found to be experimentally non-linear, figure 4(a). Good agreement is observed between the analytical model and experimental data. However, the resistivity was assumed to be linearly dependent on temperature, which leads to a small discrepancy. It is evident from figure 4(a) that longer bridges show more resistance than shorter bridges. The higher the $\alpha$ value, the lower the resistance for a bridge. For instance, the bridge with $\alpha = 0.1$ has a resistance of 16.7 $\text{K}\Omega$ for 0.12 mA current, whereas $\alpha = 0.04$ has a resistance of 49.1 $\text{K}\Omega$ for a current of 0.032 mA. The difference in the characteristics of all three bridge configurations is primarily due to their total bridge length $l$. It can be clearly seen that $\alpha \approx 0.05$ and $\alpha = 0.1$ exhibit similar characteristics, because of their same dimensions of the heater segment and they differ by a mere bridge length of 100 $\mu\text{m}$.

Figure 4(b) depicts the power–current characteristics of three different bridge configurations and were obtained using $V-\text{I}$ measurements. Similar to the $V-\text{I}$ characteristics, longer bridges dissipate more power than shorter bridges and
Power dissipation is primarily due to the current rather than the resistance as the power is contributed by the square of the current through the conducting segment. The heater power consumption is around $0.18 \text{ mW}$ or $0.12 \text{ mA}$ ($\alpha = 0.1$), allowing battery-powered operation in portable detectors. As the temperature effect was not considered in equation (6) to calculate equivalent resistivity, the $V-I$ and $P-I$ curves slightly deviate from the measured data. In our experiments, the microbridges have been operated carefully to avoid melting at a sufficiently high current.

Figure 5 graphically illustrates the relationship between the maximum temperature and applied current. The plot is obtained using equation (29), which suggests $\theta_{\text{max}}$ is a function of current and the length of the segments. In general, increasing the current through the bridges will increase the temperature, which will increase the resistance and consequently the power dissipation. In other words, the maximum temperature at the centre of a bridge keeps increasing for increased current values.

In addition, longer bridges have the maximum temperature at the centre rather than the shorter bridges. Otherwise, the lower the $\alpha$ value for a given current, the higher the obtained temperature. This statement is well supported from figure 3(b) and the obtained low-temperature range is in good agreement with the fitted value of $\zeta_1$. Moreover, the maximum temperature

5. Conclusions and future perspectives

This paper provides an exact analytical solution to the two-layer multi-segment suspended bridge structure under steady-state condition. The model is validated by fabricating and characterizing a prototype under ambient conditions. The experimental results agreed well with the analytical model. This work would benefit a number of applications that need a microheater for low power consumption. In addition, we believe this analytical model will aid many thermal applications and in all types of heterogeneous solids. Moreover, this model will be a useful methodology for the thermal design of Joule-heated microthermal sensors. Future work will involve the extension of the present model to transient heat transfer analysis for the two-layer multi-segment suspended bridge structures. Furthermore, temperature-dependent resistivity will be accounted into the model and the non-linear behaviour could be studied in the near future.

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