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Low-power printed micro-hotplates through aerosol jetting of gold on thin polyimide membranes

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ABSTRACT

We report on patterning of miniaturized gold (Au) based micro-hotplates reaching high temperature at lower power consumption than ever reported using aerosol jet printing. Efficient heating (i.e. ~12 °C/mW) was achieved by reducing the effective heating area and the thickness of the polyimide substrate. Au nanoparticles solution was used for printing heaters of two different sizes, i.e. 500 × 500 μm^2 and 150 × 150 μm^2. These double meander heaters were patterned on a 50 μm-thick polyimide substrate implementing 5 μm-thick membranes using laser etching. Finite element simulations were used to optimize the thermal design of the devices. They exhibit a power consumption at 250 °C of 39 mW and 22 mW for the larger and smaller heater design, respectively. These results indorse the significance of aerosol jet printing process at high resolution to realize high temperature and power efficient micro-hotplates on foil for applications such as; in portable gas and chemical sensors, thermal metrology and mapping, localized heating, thermal actuators and microfluidics etc.

1. Introduction

Printing electronic devices on polymeric substrates have witnessed significant growth in recent years, with keen interest in developing cost-effective manufacturing routes and processing of diverse materials [1–3]. The whole printing process involves few steps for patterning of solution based materials, which make them unique and advantageous for reduced materials' wastage and manufacturing cost [2,4,5]. The early developments have resulted already in various proof of concept devices which lay an effective platform for future flexible and foldable electronic systems [6–8]. The various attractive electronic devices developed on polymeric substrates so far also include micro-hotplates, which are central to a range of different sensing applications [8,9].

Micro-hotplates are self-heating devices, working on the principle of Joule's heating due to resistive metallic structures, conventionally developed using silicon (Si) micromaching technologies [10,11]. Other approaches have also been proposed integrating micro-hotplates on porous silicon structures and glass substrates [12,13]. Micro-hotplates on polymeric foils have unique properties such as lower thermal conductivities, mechanical flexibility and lightweight distinguishing them from rigid silicon wafer based devices [8,14,15]. Printing is preferred on foils for its simple and cost-effective manufacturing compared to state of the art photolithography and etching techniques commonly practiced for Si based micro-hotplates. Inks containing silver nanoparticles are usually practiced for printing micro-hotplates on plastic substrates [8,14,16,17], however, they have serious issues of oxidation and non-stability due to electromigration under higher temperatures [18]. Printing of a stable metal such as gold (Au) has been considered to allow better stability at variant operating conditions. Limited work has been reported on printed Au micro-hotplates on polymeric substrates such as polyimide (PI). One such approach was based on an inkjet printed heater on the backside of a 50 μm thick substrate with an effective area larger than 2 mm^2 [19,20]. These devices have been reported to consume higher power i.e. 590 mW at 300 °C [19], which is much higher than the power consumption of miniaturized micro-hotplates developed on thin SiN (silicon nitride|) membranes using standard microfabrication technology [21,22]. Therefore in this research, we focus on reducing the overall size of the microheater as well as printing on membranes as thin as 5 μm to achieve low power consumption for printed hotplates.

PI substrate with 50 μm of thickness was used in this study, which was thinned down to 5 μm using laser etching for improved thermal insulation. A high resolution digital printing technique i.e. Aerosol jet was employed to minimize the effective size of the micro-hotplate, in comparison to inkjet printed reported in the previously reported work [16,17]. Under ideal conditions, aerosol jet technique is capable of printing down to 10 μm wide patterns, making it of interest for high resolution patterning of metallic lines. Using this printing technique, we

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have achieved the printing of 25 μm wide gold line patterns which were implemented in double meander heater designs. Characterization of mechanical (i.e. adhesion) and electrical-thermal properties (resistance, thermal coefficient of resistance, power consumption) of the heaters was performed. Power consumption and temperature distribution was characterized using scanning thermal microscopy (SThM). The best performing device exhibited a power consumption as low as 22 mW for an operation temperature of 250 °C. This result is more than an order of magnitude lower than what has been reported before for printed hotplates and comparable with the power consumption achieved for devices fabricated using clean room technologies [11,15]. The simple additive processing proposed makes the technology promising for various applications, such as chemical, gas and flow sensors, micro-fluidics, actuators, low-power handheld and portable devices, and large area heating mats.

2. Design and materials for microhotplates

Micro-hotplates are thermally isolated structure to achieve high thermal efficiency based on suspended thin dielectric membranes. Low power consumption is an important factor of micro-hotplates, which is determined pre-dominantly by the materials thermal properties, size and operating temperature. Different geometrical structures such as spirals, meander, square, etc. are practiced for the heaters design driven by the desired applications and the quest for uniform thermal distribution. Among these, double meander is commonly used to achieve homogeneous heating of the effective area. Fig. 1(a and b) shows schematic diagrams of the top and cross-sectional view respectively of the double meander micro-hotplate. The most important and critical features considered for printed micro-hotplates is its power consumption and robustness during operation [10]. Reliability and life cycle is improved by selecting proper materials. Heater material must sustain high current densities and be resistant to oxidation while the polymeric substrate have to withstand high temperature. Another important factor is the physical adherence and attachment of the heater material to the hosting substrate. Nonetheless, reducing power consumption is critically demanding in current scenario of a greater surge in handheld testing and transducer devices [11,23,24], where micro-hotplates are considered to be the core transduction element of the system. Two of the main factors contributing in lowering down the power consumption are, reducing the effective area of the micro-hotplate and developing micro-hotplates on thin dielectric membranes. These two strategies are successfully implemented already using conventional microfabrication technologies i.e. photolithography on Si wafers and polyimide foil [22,25]. However, in this research we present suitable materials and processes to achieve these milestones by printing miniaturized micro-hotplates on polymeric substrates.

2.1. Materials

2.1.1. Substrate selection

Polyimide (PI) Upilex-50S was selected as substrate for the micro-hotplates development. The 50 μm thick PI has good mechanical stability and chemically inert to solvents used in printing solutions. The lower thermal conductivity i.e. 0.29 W/m/K of this PI material and stability at higher temperatures i.e. ~400 °C is one of the attractive features, strictly needed for micro-hotplates applications, especially for operation of metal oxide sensors [19]. Thinning of the polyimide substrates to form membranes was performed to achieve lower power consumptions.

2.1.2. Gold (Au) nanoparticles solution

Very few conductive metals have been introduced so far in printed electronics on polymeric substrates [1,5,26–29]. Certain limitations such as synthesis of a stable colloidal solution, which is reliable for printing and most importantly the sintering of these material at compatible temperatures of polymeric substrates are needed to be overcome [2]. Commonly practiced metals are copper and silver nanoparticles based solutions, however both are prone to oxidation. Besides oxidation, they are also highly unstable at higher temperatures and current densities resulting into degradation through electromigration and mechanical breakdown by cracking or peeling off from the substrates. Compared to these, gold is more stable, resistant to oxidation and electromigration while maintaining its physical and electrical properties at elevated temperatures).

Gold has already been experimented through electroplating on Ag

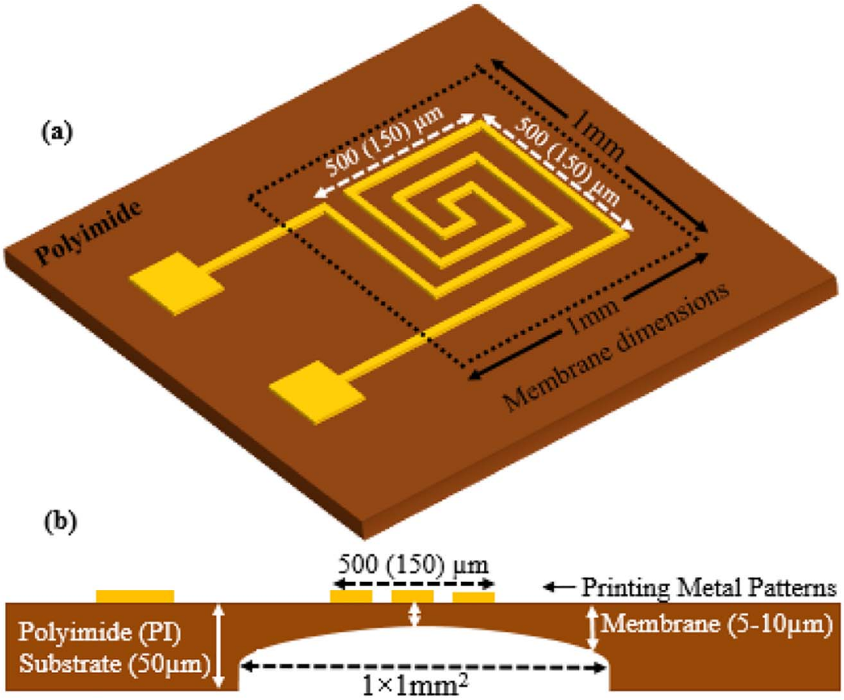

Fig. 1. (a) Schematic of double meander micro-hotplate, dashed lines representing the membrane size (b) Side View schematic of micro-heaters with metal patterns and membrane.