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Study of bending reliability and electrical properties of platinum lines on flexible polyimide substrates

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ABSTRACT

We have experimentally studied the variation in electrical resistance of flexible platinum lines patterned on polyimide foil when they are subjected to circular bending constraints. The lines were patterned by means of standard photolithography and sputtering deposition. Two different photolithography masks were used for comparative evaluation: an un-expensive transparency mask and a standard chromium mask. Measurements of the temperature coefficient of resistance (TCR) and time stability of the resistance have been acquired for lines bent down to 1.25 mm radius of curvature on a customized bending setup, showing good reliability results. The robustness of the lines has been also assessed by registering their change in resistance while bending at different radii of curvature. The lines showed reliability issues for radii of curvature below 1.25 mm, presenting a resistance variation of 19% for transparency mask-fabricated lines and 9% for chromium mask-fabricated lines. The worse reliability performances of transparency mask lines, compared to the chromium mask ones, was found to be due to their imperfect edges, which promoted the formation and propagation of cracks during bending. The results of the experiments in this work permitted to compare the performances of flexible conductive lines with different geometry and fabricated with two different masks, establishing quantitative and qualitative bending limits for their appropriate operation in flexible electronics systems.

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1. Introduction

There is a recent interest in polymer-based electronics due to its low cost, less demanding processing conditions and unique mechanical capabilities. Polymer-based electronics, also called plastic-electronics, consists of the utilization of polymeric materials as substrate for electronic circuits and systems. Polymers open new opportunities in the field of microsystems engineering, especially in those applications where price, light weight or mechanical rigidity are limiting factors. Large area electronics, biocompatible systems, environment-friendly devices or devices subjected to mechanical deformation are some examples of these kinds of electronics that are now envisaged with more optimism. Polymer electronics presents some potential advantages in these respects, compared with standard electronics: flexibility and/or stretchability, lower price (compatibility with large scale process such as roll-to-roll), lower weight, transparency, recyclability, biodegradability, and biocompatibility [1–3]. Conductive lines forming interconnections and devices are usually a key point in the performance of electronics because their high surface to volume ratio make them vulnerable to thermal interface-induced and diffusion related damage [4]. The reliability aspect of conductive lines becomes even more critical for lines patterned on flexible substrates, such as polyethylene naphthalene (PEN), polyethylene terephthalate (PET) or polyimide [5], which are subjected to bending and deformation, generating extra stress on the lines [6,7]. The resulting damages in the lines would decrease their conductivity or even break them definitively. Because this issue plays an essential role in the overall system operation, special care has to be taken when designing flexible conductive lines for each kind of application.

The reliability of thin film metal lines has been widely studied on traditional rigid substrates [8] and also some work dealing with strain rate of freestanding Pt films can be found [9]. Regarding the reliability of electronics on flexible substrates in general, the mechanics of thin films on plastic foils in the context of transistors was addressed in [10]. Also, the failure modes of inorganic materials patterned on plastic foils and subjected to bending were defined in relation to their geometry in [7,11]. More specific and application-related studies characterized the effect of bending in the operation of organic FETs fabricated on PEN [12], in the capacitance of chromium/gold interdigitated electrode structures

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patterned on polyimide and polyetherimide [13], or in the resistance of ITO deposited on PET substrate [14] for flexible display technology. However, to the best of our knowledge, the mechanical reliability of Pt lines deposited on PI or in other polymeric substrate in general has never been investigated.

Platinum has been traditionally used as temperature sensing material due to its ability to offer a very linear and high response against wide changes in temperature. Moreover, platinum is chemically inert (desirable in the field of sensing) and easy to process, even on polymeric substrates. Combining the two former properties, sensing platforms including gas and/or temperature sensors have been fabricated by patterning platinum onto flexible polymeric foils: flexible thermometers consisting of platinum resistors deposited onto polyimide have already been reported in [15–18]; other flexible sensing platforms integrating Pt capacitive gas sensors together with thermometers on polyimide substrate can be also found in the literature [18]; finally, metal–oxide (MOX) gas sensors have been developed by patterning Pt lines on polymeric substrate to form flexible micro-hotplates [19]. For the most part of the previous applications, the capability of operating at high temperature is indispensable: MOX gas sensors need high temperatures of around 300 °C to work properly, whereas that for thermometers, the higher is the temperature that they can withstand, the wider is their sensing range and application field. Because of that, the material used as substrate in all the previous examples was polyimide. Polyimide is a polymer that possesses very high thermal stability, with a glass transition temperature, T_g, ranging from 350 to 500 °C, far higher than its others polymers counterparts. Furthermore, polyimide presents good chemical stability, commercial availability and has already been widely used in electronics.

In this work, we studied mechanical and electrical reliability issues for platinum lines on polyimide substrates when they are subjected to circular and static (no cycling) bending. The selected materials are of general interest in the field of flexible electronics and sensors operating over a wide range of temperatures: thermoresistors, micro-heaters for gas sensing, micro-heaters for flow sensing, etc. Those materials, specifically thin-film platinum conductive lines with a very thin titanium adhesion layer, sputtered onto polyimide substrate, have indeed been previously used in our group for the fabrication of temperature and gas sensors [18,19]. The assessment of the bendability of such devices served as an initial motivation for the current work. The use of platinum as functional material involved the use of standard photolithography for patterning. Then, we considered interesting to fabricate the lines using two different masks, a standard chromium mask and a simpler transparency mask, for performances comparison. The transparency mask is well suitable for low resolution patterns, but produced lines with wavy and imperfect edge. Resistance measurements of flat and bent lines were taken at different temperatures to establish their temperature coefficient of resistance (TCR) and its variation upon bending. Following, we have studied the time stability of the lines resistance subjected to bending stress. Finally, the mechanical robustness of the lines was determined by subjecting them to bending at different radii of curvature. The tests were all carried out in a customized bending set-up. The differences between lines fabricated with transparency mask (transparency mask lines from now on) and chromium mask (chromium mask lines) have been highlighted for every experiment along the whole work. As an outcome, facing the challenge of achieving performing and mechanically flexible electronic systems, an experimental procedure has been described to establish practical working limits for bending thin film platinum lines on polyimide substrates. Such lines are of high interest for the development of flexible resistance temperature detectors.

2. Material and methods

The material used as substrate was 50 μm-thick polyimide (*UPILEX*® 50*S* from *UBE*). Two sets of lines were fabricated by means of photolithography, metal sputtering and lift-off. For the first set, a transparency mask was used in the exposure step of the photolithography process whereas for the second set, we used a chromium mask. Both sets of lines were made of a layer of platinum, with a thickness of ∼180 nm for the first set and a thickness ranging from 110 nm to 120 nm for the second one. Underneath the platinum layer, a very thin layer of titanium around 25 nm-thick for the first set of lines and 15 nm-thick for the second set has been included to enhance the adhesion between the platinum and the substrate. The potential application of the lines as flexible sensors and actuators undergoing a wide range of temperature (like thermometers, micro-heaters, etc.) justifies the materials choice.

Fig. 1 depicts every step of the lines fabrication process. First of all, the polyimide foil has been bonded to a silicon wafer, used as a holder. Then, two different kinds of resist, LOR and S-1813 photoresist have been spin coated over the polyimide foil. The two different sets of lines have been patterned on the resists by UV exposure of the S-1813 photoresist, using either a transparency or a chromium mask, and selectively developing it. Subsequently, the underlying LOR resist is etched isotropically in the same developer. As a result, a small wedge is formed under the LOR resist. This wedge shape prevented the formation of "ears" of metal during the final lift-off step. Following a 1 min long argon plasma pretreatment of the surface of the substrate, a thin film (15–25 nm) of titanium and a thicker one (110–180 nm) of platinum has been sputtered on the wafers. The titanium layer is necessary to increase the adhesion between the platinum lines and the polymeric substrate. The sputtering was carried out in a system *Pfeiffer Spider* 600. Finally, the remaining photoresist has been lifted-off giving as a result the metallic structures patterned on the substrate. The last steps were the removal of the polyimide substrate from the silicon wafer and the cleaning of the final devices with isopropanol and de-ionized water.

The mean resistivity of the lines at room temperature was 40 ± 6 μΩ cm, which lies between the resistivity of Pt and Ti and is comparable to previously reported similar films [20]. As presented in Table 1, the layout of the fabricated lines were 10 or 25 μm-wide, and their length ranged from 1 mm to 23.4 mm. The length of the lines was designed to facilitate their circular bending over the half cylinder – shaped accessories with different radii of curvature shown in Fig. 3(b). The lines were compelled to bend along their whole length over the surface of the accessories keeping their contact pads as flat as possible. The selected radii of curvature were 0.325 mm, 0.75 mm, 1.25 mm, 2.5 mm, 5 mm and 7.5 mm in an attempt to cover a wide range of radii of curvature from infinite (flat device) down to 0.325 mm selecting intermediate relevant values. The minimum radius of curvature was imposed by the minimum line length that we were able to manipulate and clamp in the bending set-up. In any case, the addressed range of radii is suitable for the most part of practical situations in which a flexible device is compelled to adapt to arbitrary shaped objects such as vehicles fuselage or chassis, machinery parts, wires, probes, food items or even parts of the body.

The width and thickness utilized are consistent with the typical values utilized in previous works (both in our group and other groups) where miniaturized thin film gas and temperature sensors have been fabricated by patterning platinum onto flexible polymeric foils [13–17]. These values yielded reasonable resistance for thermoresistors and are in the order of the typical resolution of microfabrication techniques. The lines were kept thin enough to allow flexibility, avoid high stress during deposition and

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