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Effects of tensile stress on electrical parameters of thin film conductive wires fabricated on a flexible substrate using stencil lithography

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ABSTRACT

We report for the first time the results of tensile stress testing of thin film conductive structures patterned by stencil lithography on a PI substrate. The goal of this investigation is to determine the effects that mechanical deformation occurring in real applications can have on electrical parameters of metal interconnects in flexible electronic circuits. The thickness of thin film gold conductors is of the order of 10 nm, while their lateral dimensions are in the micrometer range. Electrical parameters of thin film conductors are measured under uniaxial tensile stress and in the relaxed state after subjecting them to a number of stretching and relaxation cycles. SEM imaging of the test structures was used for observing of possible changes in thin film surface morphology caused by the applied tensile stress.

1. Introduction

Traditional electronic devices are mostly built using rigid materials, from semiconductor substrates to printed circuit boards, and enclosures. However, new applications arise where mechanical deformability of electronic circuits and devices is desirable or even necessary, which led to the development of flexible electronics. This emerging field includes bendable and rollable, as well as stretchable electronics. Applications include skin mounted or implantable biomedical devices, wearable electronics, rollable and bendable displays, sensors, solar cells etc. [1,2]. The use of polymer materials (PI, PEN, PET, PDMS) as substrates enable electronic circuits and components to be flexible in order to conform to the shape of other objects, to change their shape due to mechanical movements, and to better withstand stress under mechanical load. There are other advantages of polymer substrates, such as light weight and low cost. However, due to their low thermal stability and incompatibility with solvents, the use of conventional IC fabrication processes is difficult, so alternative techniques should be applied, such as stencil lithography [3].

Flexible electronic circuits will integrate different components (transistors, electrical interconnects, etc.) onto a polymer substrate that may be subjected to different kinds of mechanical deformation (elongation, bending, torsion, etc.), depending on their application. The deformation may occur once or many times after relaxation or it can happen in a different way. Under such operating conditions, the main challenge is to maintain the integrity, functionality and reliability of flexible electronics. Therefore it is necessary to investigate the effects that mechanical deformation occurring in real applications can have on electrical parameters of components of flexible electronic circuits.

Various studies have been performed of the electrical characteristics of components on flexible substrates. Characterization of electrical parameters of organic TFTs on PI substrates fabricated using stencil lithography, as well as of TFTs fabricated on PDMS, was reported earlier [4,5]. The influence of cyclic mechanical bending on electrical components (gold conductors, transistors) obtained by direct nanoimprinting of metallic nanoparticles on PI substrate using PDMS mold is also described in the literature [6].

In flexible electronics electrical interconnects are realized as conductive thin film structures patterned on a polymer substrate. Fabrication of conductive wires on PI, PEN, and PET substrates by using stencil lithography was reported earlier [7], as well as the results of resistivity measurements of test structures which were not subjected to mechanical deformation. In this paper we present for the first time the results of further electrical and mechanical characterization of thin film gold (Au) conductive wires patterned on the PI substrate, which were subjected to uniaxial tensile stress, as well as to an increasing number of tensile stress and relaxation cycles. We investigated the consequences of stress on much smaller thin film conductive patterns, fabricated on a different flexible substrate and/or using a different fabrication technique than it was reported in the existing literature [6,8,9]. The range of applied strain corresponds to the stresses that occur in practical applications of flexible electronics.

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2. Test structures and experimental setup

Two types of analyzed test structures are shown in Fig. 1, with the corresponding stencils. The stencils are low stress SiN membranes supported by bulk Si [7]. The test structures consist of thin film conductive wires and contact pads fabricated by e-beam evaporation of Ti/Au bilayer through stencil apertures on a flexible 12 μm thick PI substrate. The type A structures (shown in Fig. 1b) are made of 10 nm/60 nm Ti/Au films, while the type B structures (Fig. 1d) consist of 5 nm/40 nm Ti/Au layers. Fabrication of such electrical conductive structures on polymer substrates was described earlier [7]. The samples prepared for investigation are in the form of PI stripes with six test structures of the type A or B on each, with various lengths and widths of the conductive lines. The test structure dimensions are as designated in Fig. 1, where l_1, l_2, l_3 and l denote the length of the conductive line sections between the junction points A and B, B and C, C and D, and E and F, respectively.

Inspection of the structures after fabrication and measurement of dimensions of the fabricated Au wires are performed using the optical microscope Nikon Eclipse 2000 and the dedicated software, prior to any electrical measurement or application of tensile stress.

The experimental setup for measurement of electrical resistance of Au thin film conductors, based on the 4-wire method, consists of the precision semiconductor parameter analyzer HP 4156A and the probe station for electrical connection to contact pads of test structures.

Three series of measurements of metal interconnects resistance are performed: before stretching, when the sample is under tensile stress along its length, and also when the sample is in relaxed state after subjecting to a certain number of stretching and relaxation cycles.

Subjecting the PI sample with Au test structures to different levels of uniaxial tensile stress was performed using the Tensile Stress Testing (TST) System 350 made by Linkam Scientific Instruments (Fig. 2). The mode of operation of the TST (free stretching, step motion or cyclic motion) and the parameters of sample stretching (the absolute elongation and the stretching velocity) were set using the software Linksys 32. The TST with a sample mounted in it was placed inside of the probing station, where the probes were placed on the test structure pads for 4-wire electrical measurements.

The same experimental setup was used for testing of the mechanical endurance of thin PI substrates, since the TST can measure the dependence of the force exerted on the PI stripe during the stretching on absolute elongation.

The scanning electron microscope (Zeiss LEO 1550 Gemini) was utilized for observing the surface morphology of the Au thin film interconnects before and after stretching.

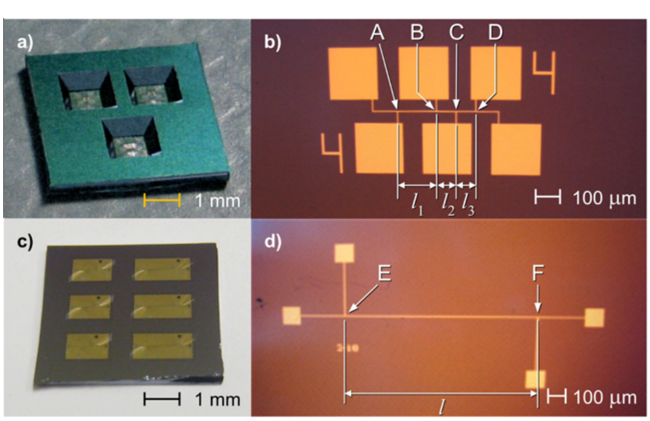

Fig. 1. (a) Photograph of a type A stencil, (b) photomicrograph of a type A test structure (10 nm/60 nm Ti/Au; total length ($l_1 + l_2 + l_3$): 160 or 320 or 480 μm, width w: 2 or 4 or 6 μm), (c) photograph of a type B stencil, (d) photomicrograph of a type B test structure (5 nm/40 nm Ti/Au; length l: 1 or 2 mm, width w: 2 or 5 or 10 μm).

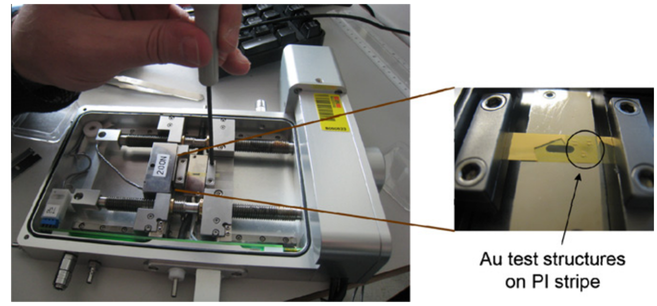

Fig. 2. Photograph of the sample stage (with a motor and a force sensor) of the Tensile Stress Testing System 350 (Linkam Scientific Instruments) used for stretching tests. The magnified detail shows a PI sample with Au test structures, mounted in the TST.

3. Results and discussion

The resistance of thin film Au conductors of different dimensions fabricated on a flexible substrate is measured before stretching the samples. Based on the results of the resistance measurements and the measured dimensions of Au wires, the average resistivity values are calculated: $\rho_A = 5.62 \times 10^{-8}\ \Omega$m for the type A structures, and $\rho_B = 5.88 \times 10^{-8}\ \Omega$m for the type B structures. Compared to the resistivity of bulk gold, which is $2.2 \times 10^{-8}\ \Omega$m, the obtained values are 2.55 and 2.67 times greater, respectively. Previous experiments [7], with a similar, but thicker test structure (10 nm/150 nm Ti/Au on PI) yielded wire resistivity of $3.3 \times 10^{-8}\ \Omega$m. However, other authors reported resistivity values significantly higher than the ones we determined [6,8,9]. This discrepancy in thin film resistivity most probably originates from the difference in the structure of Au films fabricated using different techniques and/or different substrates. The Au film that we fabricated on PI is of a more uniform structure, with densely distributed grains, while the film on PDMS is in the form of a network of Au ligaments across randomly distributed cracks [8,9].

The objective of the second series of measurements was to investigate the dependence of the resistance of thin film Au wires on the strain ε. The mode of operation of the TST was set to "step movement" using the software Linksys 32, in order to gradually elongate the sample (a PI stripe with Au test structures) for one chosen step between two consecutive measurements. The values of the strain were chosen by setting the parameter "step movement" in the software (defining absolute elongation of the sample), for the known initial length of the PI stripe, L (L was measured using a caliper before stretching). Measurement of the resistivity was taken each time the elongation of the sample by the TST reached a set value, i.e. when the strain was increased for the chosen step. In Fig. 3 the experimentally obtained dependence of the resistance on strain is shown (the line with squares). The measurement was performed on the type A structure, whose actual length ($l = l_1 + l_2 + l_3$) and width are 320 μm and 4.4 μm, respectively. Within the limit of elastic deformation of the PI stripe, the change of the resistance was less than 6%.

The measured resistance increases with the increase of ε, as it is expected according to the theoretical dependence $R_{theory}(\varepsilon)$ (dashed line in Fig. 3) obtained assuming the change of R is a result of the change of dimensions of the structure caused by the uniaxial tensile stress,