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Delamination phenomena in aluminum/polyimide deformable interconnects: In-situ micro-tensile testing

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ABSTRACT

The deformation and failure mechanisms of metal/polymer electrical interconnects with S-shaped planar meanders are investigated. Samples consist of 1 μm thick aluminum conductive coating evaporated on a 10 μm thick polyimide substrate. Uniaxial tensile tests up to 40% stretch with in-situ optical and scanning electron microscopy (SEM) were performed to assess the effects of different meander geometries on the local mechanics. As a consequence of the large strain experienced by the underlying polymeric substrate, two different delamination modes were observed at the metal/polymer interface, namely, (a) shear-based and (b) buckling-based delamination. Mechanisms (a) and (b) are activated depending on the specific meander geometry: interestingly, a crucial role was played by the length of rectilinear arms, which was shown to influence the extent of transverse contraction experienced by the interconnect. Upon increasing stretch, in-situ SEM observations revealed detrimental effects related to the interfacial failure, as metal fracture localizes in the delaminated areas. Experimental results suggest that, in addition to the need of surface treatments aimed at improving the metal/polymer interface adhesion, it is also crucial to conceive optimal geometrical designs to achieve mechanical reliability of stretchable interconnects.

1. Introduction

Flexible and Stretchable electronics refer to a new class of devices whose key attribute is the ability to be bent and stretched undergoing large strains (≫1%) keeping their function under mechanical loading as required by the applications. In particular, deformable electrical interconnects are pivotal components for large area stretchable and flexible devices, which are conceived as grids of sensing elements whose function is to provide spatially resolved measurements on deformable bodies such as the case of applications in the biomedical field [1,2,3]. Nevertheless, matching the mechanical response of the metal film and the polymeric substrate still opens some issues related to functional failure [4,5,6]: to address the associated challenges in material science, it is instrumental to improve the mechanical reliability and hence the electrical functionality [7] of deformable interconnects. Cracking of the metal films and interface delamination phenomena represent the most critical mechanical issues for metal/polymer systems. In particular, previous studies have shown that in metal/polymer systems subject to stretching, the metal film first develops cracks perpendicular to the tensile direction at low strains [8,9]. Upon further loading, compressive transverse stresses arise in the film strips due to a Poisson's ratio mismatch between the substrate and the film, causing delamination and buckling in a direction perpendicular to the tensile direction [10,11,12,13]. As the metal film delaminates and becomes freestanding, the benefits related to the interaction with the compliant substrate are lost; indeed, experiments have shown that a freestanding thin metal film usually fractures at a smaller strain with respect to thin metal films bonded to a polymeric substrates [14,15,16]. The low ductility of a freestanding metal film results from local thinning. For a sufficiently thin film with exposed free surface, dislocations readily escape from the surface [17,18]. Subsequently, the metal does not harden appreciably and even a small perturbation in the metal film thickness promotes necking formation. Although metal cracking and buckling induced by transverse compression have been widely reported in literature, these studies generally refer to fully coated metal/polymer systems and hence they do not provide a comprehensive knowledge on patterned metal films onto polymeric substrates, which are the leading choice for deformable interconnects developed by microfabrication technologies. In the coplanar technology [19,20], in fact, the deformability of the device is

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achieved by means of stretchable interconnects able to withstand the high deformations requested by the specific applications. Metal interconnects featuring suitably designed geometry have been explored, proposing different structural designs [4,21], among which S-shape geometry has been widely used [22,23,24,25]. This approach is, up to date, one of the most promising strategies to achieve extremely large strains (>200%), accommodated by the meander in-plane bending [26], with constant and high conductivity, depending on the selected materials ($35 \div 60 \cdot 10^6$ S/m) [27,28]. Several recent studies addressed new breakthroughs in the mechanical reliability of metal/polymer systems, providing increasing knowledge on the specific issues of patterned deformable interconnects [4,29,30,31,32]. Numerical analysis on the deformation behavior of S-shaped interconnects allowed to interpret experimental evidences of extreme stretchability by means of solid mechanics arguments [33,34]: upon stretch of the polymeric substrate, the meandering structure causes the strain field to become non-homogeneous nearby the interconnect, relieving most of the stresses experienced by the metal conductor. Normally, this mechanism postpones metal fracture, thus extending the effective stretchability of the device. Nevertheless, combined experimental and numerical studies [5] have shown that, though stress peaks do not trigger the development of cracks in the metal, they may concentrate at the metal/polymer interface and go beyond critical tractions, leading to interfacial delamination. Naturally, the non-homogeneous stress distribution greatly depends on the interconnect geometry, which thus dictates whether and where delamination may occur. In this paper the local deformation mechanism of aluminum/polyimide deformable S-shape electrical interconnects subjected to uniaxial tensile stretch, characterized by a moderate stiffness mismatch ($E_{Al}/E_{PI} \sim 20$), have been investigated. The local mechanics of this material system is suitable to investigate the issue of stretch-induced metal/polymer delamination, which is well reported in the literature [35,36]. Accordingly, we present an experimental study which explores the deformation modes and associated mechanical failures of stretchable aluminum/polyimide interconnects; the study is carried out by means of tensile tests with in-situ SEM as well as optical imaging. The role of the geometrical design of the S-shaped aluminum meanders is discussed. Finite element models have been used to support the interpretation of experiments on a solid mechanics basis. The results reveal a correlation between the specific meander geometry and the failure mechanisms experienced by the interconnect. Design rules to enhance the reliability of deformable interconnects can be inferred from the specific results achieved in this work.

2. Experimental

Fabrication of devices was performed on Si 4″ substrates, single side polished. Doping and crystal orientation were not considered since wafers were used only as mechanical support during fabrication. In order to provide a repeatable adhesion of layer on wafers, a thin oxide layer (30 nm) was grown by thermal dry oxidation and treated with plasma oxygen before coating with the structural layer (Matrix Plasma Asher, power 200 W, O_2 1.5 Torr, temperature 80 °C, time 1′and 20″). The substrate (structural layer) was implemented with a polyimide film, Durimide DI115A, with a target thickness of 10 μm. In order to reduce the layer adhesion and allow the removal of devices from the SI substrate at the end of the process, wafers were treated with a primer before deposition, since the composition DI115A already includes a primer and further priming is reported to reduce the adhesion in the resist datasheet. The polyimide film was then spun with spread at 700 rpm for 4 s, sit step 10 s, spinning at 1000 rpm for 45 s. Then, soft bake was performed on hotplate in two steps for 2 min at 100 °C, and 5 min at 135 °C. Final bake of structures was performed at 350 °C for 1.5 h in order to provide the full mechanical properties of the material. Generally polyimide represents one of the material selections for deformable electronics applications with useful properties such as chemical and radiation resistance, electrical performance and mechanical stability. Its high elastic modulus and its capability to undergo large permanent deformations make it a suitable candidate as a supporting material for flexible or stretchable electronic devices. In contrast to other widely used polymers which exhibit higher compliance and elastic recoil such as PDMS, the higher stiffness of polyimide provides a better confinement and mechanical shielding for the conductive metal layers [37,38]. The metal layer was deposited by evaporation of 1 μm of aluminum (e-gun evaporation, ULVAC high vacuum coater EBX-16C) and defined by lift-off in a planar S-shape design. For this purpose, the deposition of the layer was performed after coating the wafer with Ma-N 1420 negative resist with thickness 2100 nm, followed by layer lithography and development. In order to enhance the Al adhesion to the substrate, the surface of the polyimide was activated before Al deposition with a further oxygen plasma treatment as already described above. Lift-off was performed with DMSO at 80 °C in ultrasound bath until removal was complete. The geometrical design of the interconnects is characterized by three parameters: the meander radius (R), amplitude (A) and width (W). Five different sets of the geometrical parameters have been investigated (See Table 1).

The length of the rectilinear arm A_{in} is also reported in Table 1 as it will be a parameter with mechanical relevance. Fig. 1 shows a representative sample in which the polyimide substrate and two S-shaped aluminum metal lines are visible. The devices were separated by dicing saw cutting, setting the cut depth slightly above the polyimide thickness in order to preserve the substrate integrity.

The nominal width and length of the samples were of 1.3 mm and 15 mm, respectively. The gauge length of the serpentines samples was 5 mm; furthermore, 5 mm per side has been devoted to gripping area. Micro-tensile testing with simultaneous imaging of the samples has been carried out by means of an in-house developed micro-tensile equipment (featuring a 5 N load cell and a displacement actuator with a resolution of 50 nm) with vacuum proof components, suitable for the use in SEM chamber. Optical (Olympus LEXT OLS4100, confocal Laser Scanning Microscope) and SEM (Zeiss EVO 50 EP, LaB_6 electron gun) observations have been performed during stretching of the interconnects. Displacement driven tests have been performed, at room temperature. Preliminary tests have been carried out with the purpose to assess suitable loading rates and maximum applied stretch since, differently from other polymers, polyimide exhibits a visco-elasto-plastic mechanical behavior [39,40,41], undergoing a smooth and gradual transition from the linear elastic to the irreversible (plastic like) regime [42]. Based on these preliminary tests, a displacement rate of 1 μm/s was selected in order to minimize the time-dependent contributes to the mechanical response, which would have affected the reliability of the in-situ analysis procedure.

The mechanical characterization of the single constituents aluminum and polyimide was also achieved, with the purpose to provide suitable material constitutive laws in the finite element models which simulate the stretching process. The polyimide was characterized through uniaxial tensile tests performed by means of the micro-tensile equipment described above. The sample size and testing parameters are the same as that of the aluminum/polyimide samples. A direct characterization of the aluminum layers could not be achieved, as standalone material samples do not exist. Aluminum layers evaporated on Si substrates having a thickness comparable to that of the

Table 1
Geometrical parameters for the tested S-shaped interconnects.

Distance within meanders A_{in} [μm]	Width W [μm]	Radius R [μm]	Amplitude A [μm]	Sample identifier
30	10	20	90	W10R20A90
50	10	40	150	W10R40A150
40	20	20	120	W20R20A120
60	20	40	180	W20R40A180
90	50	40	270	W50R40A270