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Impact of geometry on stretchable meandered interconnect uniaxial tensile extension fatigue reliability

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ABSTRACT

This work investigates the impact of geometry on the reliability of a high conductivity, meandered, stretchable interconnect. Meandered copper conductor interconnects of varying geometries that have been encapsulated into a PDMS matrix, are evaluated for reliability under tensile stretching conditions to 10% elongation. We present results that support our earlier findings by experiment and FEM simulation. Following, we vary interconnect parameters related to the encapsulation geometry, such as encapsulation hardness, thickness and stretchable zone perimeter, to assess impact on fatigue life of the embedded meandered copper lines. Results confirm and refine the prior simulation findings. Combinations of interconnect geometry parameters critical for stretching reliability are identified. Among others, we find that the meander radius (R) and encapsulation thickness are strongly coupled, causing very large meanders with thick encapsulation to fail very early. We show that, depending on the design of the meander transition, the characteristic life of an interconnect can differ 50 times under moderate, 10% cyclic elongation. Finally, we indicate the significance of our findings for the design of reliable, stretchable electronic systems.

1. Introduction

1.1. Goals

The general aim of this work is to equip system level engineers with a collective notion of the reliable interconnect geometries, as well as those geometries that are detrimental or hazardous and should be avoided, or carefully monitored in a complete stretchable system. In order to provide design rules we investigate the relation between geometry and lifetime in in-plane structured metal interconnects embedded in PDMS[1] encapsulation. This work builds upon the methods and findings reported in our previous publication [1] where more detailed background as well as DOE can be found. Fig. 1(a) represents the geometry of the interconnect in concern.

In a complete system the meandered interconnect connects stiff islands hosting electronic components. This layout grants significant deformation capability and electric functionality. The concept is illustrated in Fig. 1(b) and (c). More information on stretchable systems, example applications and references can be found in the work of Vanfleteren et al. [2].

We study the effect of the meander geometry and that of the encapsulation on the time to the electro-mechanical failure of the interconnect in cyclic stretching tests. Furthermore, finite element analyses are used to explain the observations made through Weibull lifetime analysis, as well as to perform parametric sweep past the capabilities of an experiment.

1.2. Background

We are particularly interested in the structured metal interconnect of meandered shape due to the large area, conformable circuit applications in mind, which translates into the following requirements:

- Very high conductivity (generally above 10^5 S/cm, for efficient, large area, mid power circuits, e.g. light engines).

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[1] Polydimethylsiloxane

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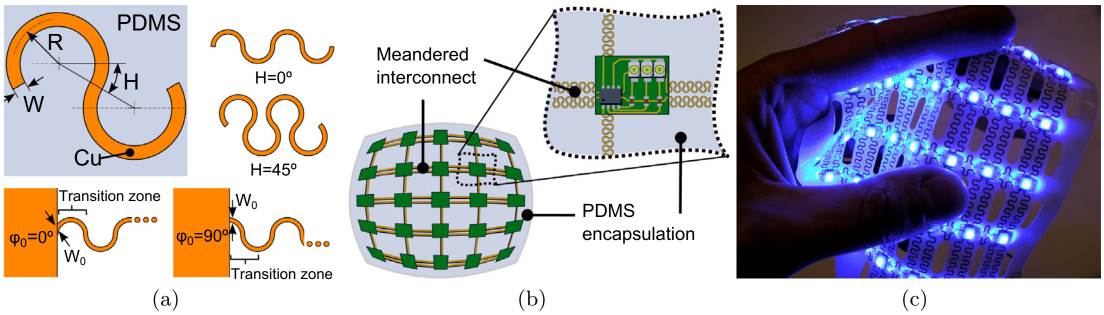

Fig. 1. (a) Meander definition and its geometry parameters. (b) Stretchable interconnect utility in a conformable system. (c) Example stretchable light engine system.

- Ease of development using standard electronics manufacturing processes and equipments (transfer to industry).
- Electrical stability under strain (no significant resistance-strain dependence and no significant resistance-wear dependence).

Reviewing the stretchable technologies developed in the recent years [3–10] we find no stretchable, conductive, composite elastomers that fulfill these requirements all at once. Only structured metals (meanders [11–14], meshes [15], yarns or buckled films [16]), forming a stretchable interconnect exhibit electro-mechanical properties that can fulfill the above mentioned requirements. In particular, in-plane meandered interconnect (Fig. 1(a)), studied in this work, even if one penalizes bulk copper conductivity of $\approx 6 * 10^5$ [S/cm] proportionally to the added current path due to meandering, delivers, what one could define as equivalent conductivity of $2.5 * 10^5$ [S/cm], for a typical geometry of $H = 30^\circ$. Approximately, this holds for any R since the running length of the meander can be shown to be independent of radius. This conductivity is still about 31 times higher than the silver nanowires based, elastomer composite solution developed by Xu and Zhu [10] – the most conductive, stretchable composite known to authors that allows resistance stability under mechanical load.

2. Materials and methods

2.1. Test vehicle

Fig. 2(a) represents a single test vehicle realized in 17 μm thick copper (Circuit Foil BF-HF-LP2) by means of photolithography, using dry film photoresist (DuPont Riston FX 920) and wet copper etching. The processing is carried out on a sacrificial FR4 carrier. The carrier is removed after embedding the top of the structured copper by 0.5 mm thick PDMS (Dow Corning, Sylgard 186), by means of liquid injection molding. Finally, the opposite side of the copper structure is encapsulated by injection molding. A detailed SMI processing is illustrated in another publication of our group [2]. The test vehicle can be divided into two functional zone types, the flexible only zones, realized by the large copper spill areas (bright areas in Fig. 2(a)) and two flexible, but also stretchable zones, containing the stretchable interconnects (transparent areas appearing darker in Fig. 2(a)). The two stretchable zones are bridged by meandered interconnects, a pair of each connected electrically in series (please refer to Appendix B (Fig. 15) for test vehicle dimensions and indication of test current paths).

2.2. Endurance test

The test vehicle, shown in Fig. 2(a), is fixed in the test setup and connected to the resistance measurement system (please see Appendix A). The reading in Fig. 2(b) is obtained by means of 4 point resistance measurement while the test vehicle undergoes repeated tensile elongation using an Universal Testing Machine (UTM). Fig. 2(b) illustrates the high electrical stability and low resistance delivered by a series chain of two, 1 cm long, copper interconnects, registered under repeated, 10% interconnect strain-a generic endurance output in this reliability study. Please note the logarithmic scale on the vertical axis. Some spread of the instantaneous reading was present due to a random noise pickup during

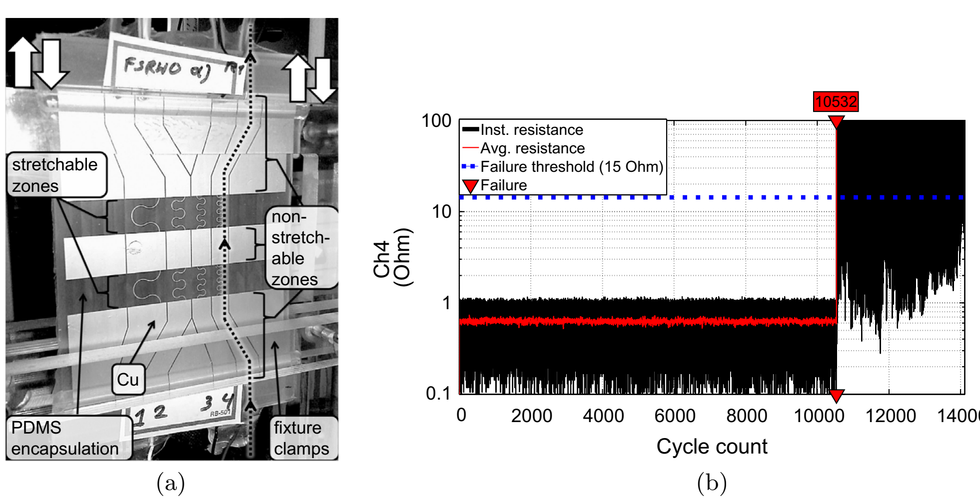

Fig. 2. (a) Test vehicle fixed in the UTM. Dotted line indicates test current path for the resistance measurement in the 4th meander chain. (b) Meandered interconnect resistance reading taken during the 10% uniaxial stretching endurance test.

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