Copper-rubber interface delamination in stretchable electronics

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COPPER-RUBBER INTERFACE DELAMINATION IN STRETCHABLE ELECTRONICS

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ABSTRACT
Currently manufacturing concepts for stretchable electronics, using undulating metallic interconnect structures on a rubber stretchable substrate, are being developed but exhibits interface delamination as a precursor to failure. In this article, the microscopic delamination mechanics of such systems are visualized and characterized using Environmental Scanning Electron Microscope images of the in-situ progressing delamination front of peel tests on two copper-rubber systems.

INTRODUCTION
Next generation microelectronic devices will be flexible, rollable and capable of extreme elongations. The latter aspect enables novel applications such as sensitive skin for robots and prostheses, health monitors to measure all sorts of human body functions, retinal-shaped photosensor arrays, and neural interfaces (Fig. 1). Stretchable electronics consist of small rigid microchips on a highly compliant substrate, circuited by metal wires which must be highly stretchable. Stretchability is achieved using mechanistic patterns. Ensuring interface integrity between the metallic lines and the rubber matrix forms a huge engineering challenge, making interface integritiy the key limiting factor in stretchable electronics development.

SUMMARY OF RESEARCH
This work characterizes interface delamination of the copper-rubber interface by means peel test performed inside an environmental scanning electron microscope (Fig. 2) for real-time visualization of the progressing delamination front (Fig. 3) and the delaminated rubber and copper surfaces (Fig. 4) during in-situ 90° peel tests, while the Work of Separation, Gc, is obtained from the measured force-displacement curves. To separate the different contributions to the delamination process, sets of delamination experiments are performed for (i) the same rubber but different Cu roughnesses and (ii) the same Cu (roughness) but different TPU and PDMS rubber systems.

FIGURE 1. Potential future applications of stretchable electronics, in order: neural interfaces, intra-ocular retinal array, and sensitive skin.
The results show that high adhesion energies are achieved for rough copper surfaces with deep ‘valleys’. For these interfaces, actual fibrillation of rubber at the peel front is observed at the micron scale, and the energy dissipation upon delamination is dominated by the formation, stretching, and rupture of ~40–60 μm-long rubber fibrils (Fig. 3). Energy dissipation in the fibrils is in close competition with delamination of the fibrils from the Cu interface.

Fibrillation was found to be enabled by hampering the debonding of rubber (fibrils) from the copper surface through an interplay of local surface area enlargement due to copper roughness, mechanical interlocking in the roughness ‘valleys’, and complex mixed-mode loading of the interface at the micron scale (out-of-plane loading on the tops and ‘valleys’ of the copper roughness extrusions versus in-plane loading on the walls of the extrusions). Therefore, the degree to which the delaminated Cu surface is still covered with rubber increases with increasing copper roughness. Remarkably, however, the remaining rubber surface coverage also increased with decreasing Work of Separation (Fig. 4) which signifies the crucial role of the rubber fracture toughness to the Work of Separation for these cu/rubber interface system.

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