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Copper-rubber interface delamination in stretchable electronics

J. Neggers*, J.P.M. Hoenfagels*, P.H.M. Timmermans†, E.J.L. van der Zanden†*, M.G.D. Geers*

*Eindhoven University of Technology, Department of Mechanical Engineering
P.O.Box 513, 5600MB, Eindhoven, The Netherlands
j.p.m.hoefnagels@tue.nl, j.neggers@tue.nl

†Philips Applied Technologies, System in Package,
High Tech Campus 7, 5656 AE Eindhoven, The Netherlands

ABSTRACT

The focus of microelectronic device development is ever more in the direction of flexible and stretchable devices. The latter enables, e.g., wearable sensors, skin-like sensor arrays, neural interfaces. Stretchable electronics consists of small rigid components in a stretchable matrix material. However it is generally observed that failure in stretchable electronic devices is strongly related to the interface integrity between metallic circuit lines and the matrix material. Therefore, the goal of this research is to obtain in depth insight into the interfacial integrity of these metal/rubber interfaces, following a two-step approach: (i) Cu/rubber bilayer interface systems and (ii) micron-scale Cu structures embedded in a rubber matrix.

To investigate Cu/rubber bilayer interface systems, a copper/rubber test system is characterized with 90° peel tests (Fig. 2), to obtain adhesion energies and rubber delamination geometries. In addition, Environmental Scanning Electron Microscopy (ESEM) is used for in-situ visualization of the progressing delamination front (Fig. 3). High adhesion energies are achieved for rough copper surfaces. It was found the interfacial integrity is largely determined by energy dissipation upon delamination, which is dominated by the formation, stretching, and rupture of ±20µm rubber fibrils. Energy dissipation in the fibrils is in competition with delamination of the fibrils from the Cu interface (Fig. 1), which in turn is governed by the complex mixed-mode loading of the interface at the micron scale (out-of-plane loading on the tops and ‘valleys’ of the copper roughness protrusions versus in-plane loading on the walls of the protrusions).

To investigate the complex loading of these interfaces in more detail, the miniature bulge test technique, a proven technique for measuring stress-strain curves of thin films, is fundamentally improved in terms of its systematic and statistical accuracy (Figs. 4 and 5). Improved statistical accuracy is achieved by measuring full field height maps using surface profilometry instead of a single interferometric measurement of the deflection of the membrane apex. Improved systematic accuracy is achieved by direct measurement of the cylindrical shape of the membrane, making assumptions regarding the boundary unnecessary. Proof of principle of this improved miniature bulge test technique will be demonstrated by presenting a meticulous characterization of the stresses and strains acting on the Cu/rubber interface. Moreover, the methodology is being expanded further to enable detailed characterization of micron-sized Cu structures embedded in a rubber matrix material, of which the first results will be presented.
Figure 1: In-situ ESEM image of a progressing delamination front of the copper rubber (PDMS) interface. The dominant energy dissipation mechanism is the rupture of the rubber fibrils. (Note > 80% of delaminated Cu surface still covered with rubber)

Figure 2: Schematic of the 90° peel test. An extra layer of copper is added to the copper/rubber system. The copper ends are loaded under tension in a micro-tensile stage while the force is measured.

Figure 3: Kammrath & Weiss 100 N micro-tensile stage that fits in the vacuum chamber of the ESEM, used to perform the 90° peel tests.

Figure 4: Schematic of the bulge test. A membrane is deformed using a pressure difference, the deformation is measured with surface profilometry.

Figure 5: A custom build bulge tester with a 1 × 6 mm membrane under the objective of a Sensofar Plµ2300 optical surface profilometer.