11th International Conference on Advanced Materials
ICAM 2009
Rio de Janeiro Brazil
September 20 - 25

Materials and designs for flexible and stretchable electronic surfaces

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Abstract – Flexible displays are imminent. Electroluminescent wallpaper, electronic skin, and speaking screens are on their way. “Flexible” electronic surfaces will be bent, rolled, shaped permanently, or even stretched over arbitrary shapes. They are part integrated thin-film circuit, part printed wiring board. Just like IC and PWBs, flexible electronic surfaces start out flat, because they are fabricated by planar technology. They are deformed as late as possible during or only after fabrication. We will lay out (1) the design criteria for electronic surfaces, (2) inspect the materials of which are they made, and (3) identify critical steps in their manufacture. Then we will describe briefly two recent developments: a flexible environmental barrier layer and metallization for electronic skin.

(1) When a flat sheet of thickness d is rolled to a radius R_0, the surfaces of the sheet are deformed by the 1-D strain of $\varepsilon = d / 2R_0$ (Fig. 1). The thinner the sheet the lower the bending strain. d and R_0 are design parameters. A device film encapsulated between two sheets with equal $E{\cdot}d^2$ (where E is the elastic modulus) in first order will not experience any bending strain. The radius to which such structures can be bent then will depend on the critical strain of the encapsulants. When a flat sheet is shaped to a “non-developable” surface, like a dome, large strains develop. The current answer is to place devices on rigid islands that deflect the strain to the surrounding substrate and interconnects (Fig. 2). When the substrate and interconnects are deformed plastically, a permanently-shaped electronic surface results. On the other hand, elastomeric substrates and interconnects (Fig. 3) lend themselves to reversibly stretchable electronic skin. These mechanical design criteria are fairly well understood.

(2) Materials may be stretched up to their critical strain $\varepsilon_{critical}$ without breaking or deforming permanently. A typical value is $\varepsilon_{critical} \cong 1\%$, which means that a 20-micrometer thick sheet can bent to a radius of 1-mm without damaging a device on its surface! While $\varepsilon_{critical}$ is a bulk property, in thin-film structures also depends on the film’s neighbors and on the strength of its interfaces with them. Device materials with high $\varepsilon_{critical}$ are an important subject of electronic materials research.

(3) Because thin electronic structures have low mechanical strength $E{\cdot}d$ they are easily deformed during manufacture, and may even break. Stress is introduced by growth out of equilibrium, differential thermal or humidity expansion, and the handling of free-standing substrates. The current response is to temporarily bond the substrate to a rigid carrier and de-bond it at the end of processing. Because eventually roll-to-roll fabrication will dominate, the processing of free-standing substrates is an important research area. Fig. 4 shows arrays of amorphous-silicon thin-film transistors (a-Si:H TFTs) made on a clear plastic foil substrate, an example of high-temperature processing on a flexible polymer substrate without incurring device fracture. It is hoped that all-organic electronics will more easily processable than thin-film silicon as they appear to withstand some plastic deformation and are processable at low temperature.

After providing an overview of these three aspects of flexible electronic surfaces we will describe briefly a new material for a flexible environmental barrier that combines toughness with the impermeability of inorganic glasses, and recent results on an elastically stretchable e-skin.

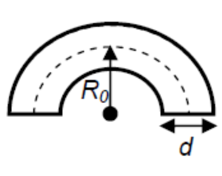

Figure 1: Bending a sheet of thickness d to radius R_0. The strain ε in the surfaces $d / 2R_0$. It is zero in the neutral plane (dashed curve).

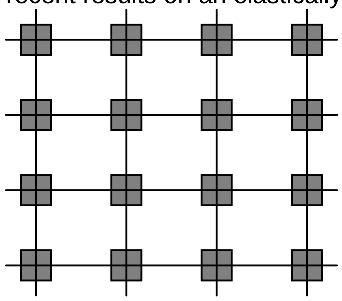

Figure 2: Schematic layout of a deformable surface, where devices are placed on rigid islands, and strain is deflected to plastically or even elastically deformable substrate and interconnects.

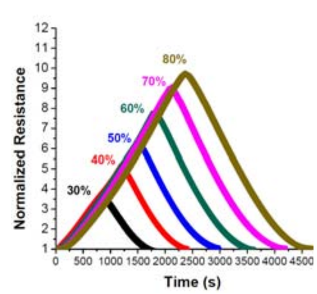

Figure 3: Normalized electrical resistance of an encapsulated stretchable gold thin-film conductor, which is stretched and relaxed consecutively up to 80% strain.

Figure 4: Photograph of a-Si:H TFT arrays fabricated on a clear plastic substrate at process temperature up to 300ºC. High process T raises the electrical stability.