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Mechanics of thin-film transistors and solar cells on flexible substrates

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Abstract

When devices are fabricated on thin foil substrates, any mismatch strain in the device structure makes the work piece curve. Any change of the radius of curvature produces a change in the size of the work piece, and thereby misalignment between individual device layers. To achieve tight tolerances, changes of curvature must be minimized throughout the fabrication process.

Amorphous silicon thin-film transistors and solar cells respond differently to externally applied tensile strain. The elastic deformation of the transistor is correlated with small increase in the electron mobility. When the tensile strain reaches ∼0.34%, crack formation starts and causes an abrupt change in the transistor performance. The performance of solar cells, on the other hand, does not change for tensile strain up to ∼0.7%. At larger strain the short-circuit current, open-circuit voltage, fill factor, and the efficiency gradually decrease.

Keywords: Amorphous silicon; Thin-film transistor; Solar cell; Flexible electronics

1. Introduction

Recent research in thin-film electronics has been focused on the replacement of the traditional rigid glass plate substrate with plastic or metallic foils. Among metallic materials, stainless steel and molybdenum foils have been utilized as substrates in the fabrication of thin-film transistors (Theiss and Wagner, 1996; Wu et al., 1997, 2002; Howell et al., 2000; Park et al., 2003) and solar cells (Yang et al., 2003). A number of plastic materials (organic polymers) also have been tested successfully in a variety of thin-film applications (Constant et al., 1994; Young et al., 1997; Burns et al., 1997; Burrows et al., 1997; Gleskova et al., 1998; Parsons et al., 1998; Lueder et al., 1998; Thomasson et al., 1998; Sandoe, 1998;

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Nomenclature

d	layer thickness (m); subscript s denotes substrate, f denotes film
FF	solar cell fill factor
J_{sc}	short circuit current (A)
R	radius of curvature (m)
T	temperature (K)
V_{oc}	open-circuit voltage (V)
Y	Young's modulus (Pa); subscript s denotes substrate, f denotes film
$Y^* = \frac{Y}{1-\nu}$	biaxial stain modulus (Pa); subscript s denotes substrate, f denotes film
$Y' = \frac{Y}{1-\nu^2}$	plain strain modulus (Pa); subscript s denotes substrate, f denotes film
α	coefficient of thermal expansion (K^{-1}); subscript s denotes substrate, f denotes film
ε	mechanical strain
ε_{bi}	built-in strain in the film
ν	Poisson ratio; subscript s denotes substrate, f denotes film
η	solar cell efficiency
σ	mechanical stress (Pa)

Carey et al., 2000; Sazonov and Nathan, 2000; Boucinha et al., 2000; Kane et al., 2001; Ichikawa et al., 2001; Hsu et al., 2002a; Brida et al., 2002; Takano et al., 2003; Cheng and Wagner, 2004; Gelinck et al., 2004; Shahrjerdi et al., 2004; Nomura et al., 2004; Monacelli et al., 2004; Choi et al., 2004).

There are three main reasons for the attraction of plastic and metallic foils. Unlike glass, the thickness of these materials can be substantially reduced while maintaining their integrity, leading to thin and lightweight products. At the same time, these thin substrates add new functionality to thin-film electronics, namely the flexing and non-planar shaping. Finally, the foil substrates lend themselves to roll-to-roll fabrication.

One faces several new issues when fabricating devices on thin foils. These are usually not encountered during the fabrication of these devices on thick plates of glass. Firstly, the devices experience variable stresses during the manufacturing process that may lead to substantial change in curvature. This leads to a change in the size of the work piece and ultimately to misalignment between different layers of the device. This is important for devices where mask overlay alignment is critical. Therefore, the radius of curvature must be carefully controlled during the fabrication. Secondly, the device application may require intentional bending, stretching, or non-planar shaping after the fabrication. Therefore, one needs to understand the behavior of thin-film devices under strain, and the fracture strain and fracture mechanism of the device layers.

Even though a detailed understanding and comprehensive mechanical theory do not yet exist, a number of experimental results are available and simple mechanical theories have been worked out (Gleskova and Wagner, 1999a,b, 2001; Suo et al., 1999; Gleskova et al., 2000, 2002, 2004; Wagner et al., 2000, 2002; Hsu et al., 2002b, 2004; Jones et al., 2002; Servati and Nathan, 2005). The purpose of this paper is to summarize the current knowledge of the mechanics of thin-film electronics with a focus on amorphous silicon thin-film technology. In the calculations we emphasize two-layer structures of substrate and film. Such structures are simple enough to be treated analytically, yet they provide a basic understanding of the mechanics of thin-film devices on flexible substrates.

2. Curvature induced during manufacturing

Thin-film devices are built on substrates layer-by-layer, often at elevated temperature. Strain develops in the structure by built-in stresses in the deposited layers (Hooke's law: $\sigma = Y \cdot \varepsilon$, where σ is stress, Y Young's modulus, and ε strain), or, upon cooling down, by the differences in the thermal expansion and humidity coefficients between the deposited film and the substrate, or between different films. The mechanics of the film-on-substrate structure depends strongly on the elastic (Young's) moduli and thicknesses of the substrate Y_s, d_s and the thin film Y_f, d_f.

When $Y_f \cdot d_f \ll Y_s \cdot d_s$, the substrate dominates and the film complies with it, as a thin-film transistor (TFT) or solar cell do on a plate glass substrate. The stress in the substrate is small, and the film/substrate couple curves only slightly, even when the film