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Mechanics of rollable and foldable film-on-foil electronics

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The mechanics of film-on-foil devices is presented in the context of thin-film transistors on steel and plastic foils. Provided the substrates are thin, such transistors function well after the foils are rolled to small radii of curvature. When a substrate with a lower elastic modulus is used, smaller radii of curvature can be achieved. Furthermore, when the transistors are placed in the neutral surface by sandwiching between a substrate and an encapsulation layer, even smaller radii of curvature can be attained. Transistor failure clearly shows when externally forced and thermally induced strains add to, or subtract from, each other. © *1999 American Institute of Physics.* [S0003-6951(99)03608-6]

The advent of active-matrix liquid-crystal displays has opened the era of large-area electronics. Many anticipated macroelectronic products, including x-ray sensors and digital wallpaper, will be far bigger than today's integrated circuits. Their widespread use will depend on a low-cost per *circuit area* rather than per *circuit function*. Part of this reduction will come from low material consumption and new manufacturing technologies. For example, thin-film transistors (TFTs) on thin foils[1,2] use less materials per unit area, and lend themselves to roll-to-roll fabrication. We show in this letter that such devices can be made particularly rugged.

We fabricated TFTs on steel and polyimide foils. The maximum substrate temperature was 350 °C for steel, and 150 °C for polyimide. All silicon-containing layers were grown by plasma-enhanced chemical vapor deposition. First, the substrate foil was coated with a 0.5 μm thick SiN_x layer. An ~100 nm thick Cr layer was evaporated and etched to create the gate electrode. Then, the TFT stack of 360–400 nm of SiN_x, ~200 nm undoped a-Si:H, and ~50 nm of (n^+) a-Si:H were grown. An ~100 nm thick Cr layer was evaporated and etched to form the source–drain pattern. Finally, the back channel into the (n^+) a-Si:H, the transistor island, and the gate contact pads were defined by plasma etching.

Figure 1 shows two transistor islands on a 25 μm thick steel foil wrapped around a pencil. When the sheet was rolled to drill bits of successively smaller radii of curvature, the transistors functioned well until some critical radii were reached: 2.5 mm if the transistors faced in, or 1.5 mm if the transistors faced out. In both cases, failure was caused by the delamination of the spin-on glass planarization layer from the steel.

To appreciate these results, let us analyze the strain in a blanket film deposited on a foil substrate. Both fabrication process and externally applied bending moment cause strain in the film. We first consider the external bending moment. Figure 2 illustrates a sheet bent to a cylinder of radius R. The film and the substrate have thicknesses d_f and d_s and Young's moduli Y_f and Y_s. When the sheet is bent, the top surface is in tension, and the bottom surface is in compression. One surface inside the sheet, known as the neutral surface, has no strain. The strain in the top surface ϵ_{top}, in the bending direction shown in Fig. 2, equals the distance from the neutral surface divided by R. Typical silicon TFT materials and steel have about the same Young's modulus. Consequently, the neutral surface is the midsurface of the sheet, and the strain in the top surface is given by

$$\epsilon_{top} = (d_f + d_s)/2R. \tag{1}$$

The minimum allowable radius of curvature scales linearly with the total thickness, assuming that the transistors fail upon reaching a critical value of strain.

Now let us look at the TFT film on a more compliant substrate such as plastic. The film and the substrate have different elastic moduli $(Y_f > Y_s)$, so that the neutral surface shifts from the midsurface and toward the film. Consequently, the strain on the top surface is reduced, as given by

$$\epsilon_{top} = \left(\frac{d_f + d_s}{2R}\right)\frac{(1 + 2\eta + \chi\eta^2)}{(1+\eta)(1+\chi\eta)}, \tag{2}$$

where $\eta = d_f/d_s$ and $\chi = Y_f/Y_s$. Figure 3 plots the normalized strain in the film versus η. Two kinds of substrates are compared: steel $(Y_f/Y_s \cong 1)$ and plastic $(Y_f/Y_s \cong 100)$. For given R and $d_f + d_s$, the compliant substrate can reduce the strain by as much as a factor of 5.

The strain in a circuit is further reduced if it is placed in the neutral surface itself, sandwiched between the substrate

FIG. 1. A 25 μm thick steel foil wrapped around a pencil. Two transistor islands on the foil are visible.

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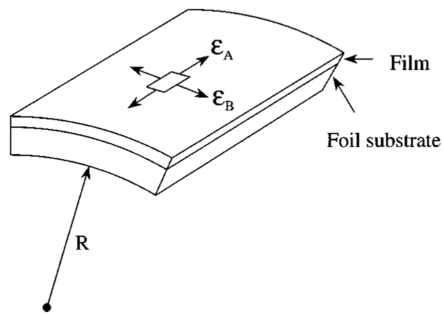

FIG. 2. A film-on-foil structure bends into a cylindrical roll.

and an encapsulation layer of suitable Young's modulus and thickness Y_e and d_e. When the stiffness of the circuit proper is negligible, the circuit comes to lie in the neutral surface if

$$Y_s d_s^2 = Y_e d_e^2. \tag{3}$$

In this case bending does not add any strain to the circuit. Consequently, the bending curvature is no longer limited by the failure strains of the transistor materials, but by those of the substrate and the encapsulation. When low modulus, small thickness substrate, and encapsulation are used, the whole structure can be bent to extremely small radii. It can even be folded like a map.

Next, we consider bending caused by the fabrication process. During TFT fabrication, the substrate foil may be held in a frame, at elevated temperatures. Upon cooling and release from the frame, the structure often bends due to film growth strain and differential thermal expansion. Several recent papers have adapted the classical theory of bimetallic strips to integrated circuits on crystalline substrates.[3–5] Here, we present aspects specific to the film-on-foil structures. The stress field due to misfit strains is biaxial in the surface of the film and the substrate. A small, stiff wafer bends into a spherical cap with an equal and biaxial curvature. However, a film-on-foil structure bends into a cylindrical roll. The cap-to-roll transition as the substrate becomes thinner and larger has been studied extensively.[4] Our substrates are so compliant that they are on the ''roll side,'' far from the transition point. Consequently, they are taken to bend into cylindrical shape, as shown in Fig. 1.

The strain in the axial direction, ϵ_A, is independent of the position throughout the sheet, a condition known as generalized plane strain. Let z be the through-thickness coordinate, whose origin is arbitrarily placed in the bottom surface. Although the deflection is much larger than the sheet thickness, the strain typically is small. The geometry dictates that the strain in the bending direction, ϵ_B, be linear in z, namely,

$$\epsilon_B = \epsilon_0 + z/R, \tag{4}$$

where ϵ_0 is the strain at $z=0$.

If the film and the substrate were separate, they would strain by different amounts, but develop no stress. Let e be the strain developed in a stress-free material. For example, thermal expansion produces $e=\alpha\Delta T$, where α is the thermal expansion coefficient, and ΔT the temperature change. One may also include in e the strain developed during film growth. Because the film and the substrate are bonded and do not slide relative to each other, a stress field arises. The two stress components in the axial and the bending directions, σ_A and σ_B, are both functions of z. Each layer of material is taken to be an isotropic elastic solid with Young's modulus Y and Poisson's ratio ν. The film and the substrate are dissimilar materials, so that e, Y, and ν are the known functions of z. Hooke's law relates the stresses to the strains as

$$\sigma_A = \frac{Y}{1-\nu}\left(\frac{\epsilon_A+\epsilon_B}{2} - e\right) + \frac{Y}{1+\nu}\left(\frac{\epsilon_A-\epsilon_B}{2}\right), \tag{5a}$$

$$\sigma_B = \frac{Y}{1-\nu}\left(\frac{\epsilon_A+\epsilon_B}{2} - e\right) - \frac{Y}{1+\nu}\left(\frac{\epsilon_A-\epsilon_B}{2}\right). \tag{5b}$$

Assume that no external forces are applied. The force balance requires that

$$\int \sigma_A dz = 0, \quad \int \sigma_B dz = 0, \quad \int \sigma_B z dz = 0. \tag{6}$$

Inserting Eqs. (4) and (5) into Eq. (6) and integrating, we obtain three linear algebraic equations for the three constants ϵ_A, ϵ_0, and $1/R$. The procedure outlined here is applicable to any number of layers, and arbitrary functions $e(z)$, $Y(z)$, and $\nu(z)$. The general solution can be developed, but is too lengthy to list here. Instead, we consider two important special cases, assuming that Poisson's ratio ν is identical for the film and the substrate.

Suppose that a film–substrate couple is bent by differential thermal expansion. The difference in the thermal strain is $e_M = (\alpha_f - \alpha_s)\Delta T$. For a stiff wafer, an equal and biaxial stress arises in the plane of the film, which causes bending. The radius of curvature R is given by the Stoney formula:[3–5]

$$R = \frac{d_s}{6 e_M \chi \eta}. \tag{7}$$

When the substrate is thin and compliant, the film–substrate couple bends into a cylindrical roll instead of a spherical cap. Choose the origin of the z axis such that $\int Y(z) z dz = 0$. Substituting Eq. (5) into the last equation in Eq. (6), we can solve for the radius of curvature. The result is

$$R = \left[\frac{d_s}{6(1+\nu) e_M \chi \eta}\right]\left[\frac{(1-\chi\eta^2)^2 + 4\chi\eta(1+\eta)^2}{1+\eta}\right]. \tag{8}$$

The term in the first bracket is the Stoney formula divided by $(1+\nu)$, a factor arising from the generalized plane strain condition. The term in the second bracket comes from the

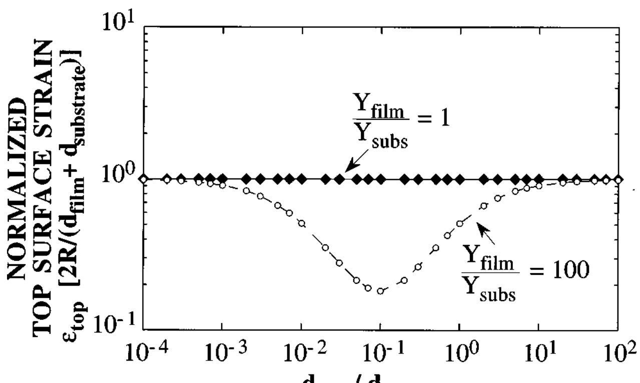

FIG. 3. Normalized strain in the film as a function of film/substrate thickness ratio. Two substrates are illustrated: steel ($Y_f/Y_s \cong 1$) and plastic ($Y_f/Y_s \cong 100$).

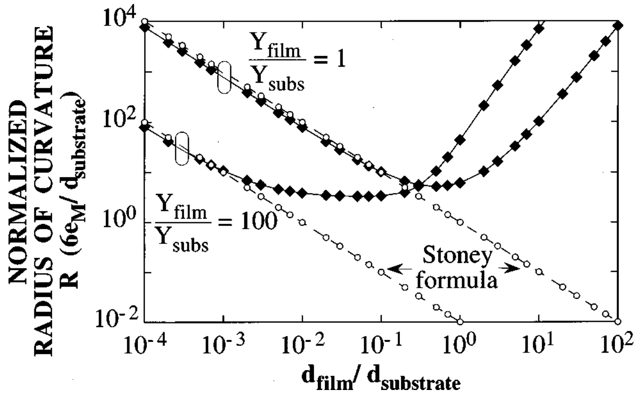

FIG. 4. Normalized radius of curvature as a function of film/substrate thickness ratio. Full lines are the solution for a cylindrical roll with $\nu = 0.3$. Dashed lines are the Stoney formula for a spherical cap formed by a thick, stiff wafer.

effect of the compliant substrate. The radius of curvature, calculated from Eqs. (7) and (8), is plotted as a function of d_f/d_s in Fig. 4. For typical TFT materials on a steel substrate, $Y_f/Y_s \cong 1$, and the Stoney formula is a good approximation if $d_f/d_s \leqslant 0.1$ and the $(1+\nu)$ factor is included. For an organic substrate, $Y_f/Y_s \cong 100$, and the Stoney formula is useful only for $d_f/d_s \leqslant 0.001$. In the specific case of a 50 μm thick polyimide substrate, $d_f/d_s \cong 0.01$, and Eq. (8) must be used.

We mentioned earlier that the transistors peel off the steel substrate at a smaller radius of curvature when the transistors face out than when the transistors face in. This behavior arises from the way the misfit strain e_M and the strain ϵ_{top} induced by forced bending add. For our sample, differential thermal expansion put the transistor material in compression, $e_M \approx 4.5 \times 10^{-3}$. (We neglect any strain during film growth.) Bending to a 1.5 mm radius adds a strain $\epsilon_{top} \approx 8.5 \times 10^{-3}$, tensile when the transistors face out, and compressive when the transistors face in. Consequently, the net strain is 4×10^{-3} tensile when the transistors face out, and 13×10^{-3} compressive when the transistors face in.

In summary, this letter gives the basic mechanics relations for externally forced and thermally induced bending of the film-on-foil devices. When TFTs are placed on the surface of a foil substrate, the smallest bending radius is set by the failure strain of the TFT materials. When the TFTs are placed on a low elastic modulus substrate, the smallest bending radius can be reduced. Furthermore, when the TFTs are placed in the neutral surface by sandwiching between the substrate and the encapsulation, the smallest bending radius is set by the failure strains of the substrate and the encapsulation materials. Consequently, extremely small radii of curvature can be achieved, which may open new applications of large-area electronics.

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