Flexible displays built on metallic or plastic foil substrates are slowly becoming a reality. Many flat panel display companies around the world have manufactured flexible display prototypes using a variety of thin-film technologies. When the substrate’s thickness \(d_s\) is reduced, its product with Young’s modulus \(Y_s\), \(Y_sd_s\), may become comparable to that of the deposited device film, \(Y_fd_f\). (A mechanical theory comparing rigid \((Y_fd_f\approx Y_sd_s)\) and compliant substrates \((Y_fd_f= Y_sd_s)\) has been published previously.) If a film-on-substrate structure with \(Y_fd_f= Y_sd_s\) is unconstrained, any mismatch strain between the deposited film and the substrate forces the structure to roll to a cylinder with the film facing outward (film under compression) or inward (film under tension). When flattened for circuit fabrication, the work piece now has different dimensions compared to the substrate before film deposition. Hence, in general, the curvature of the work piece and its dimensions change during the fabrication of amorphous silicon thin-film transistors (TFTs) on freestanding Kapton polyimide foils. This change affects the alignment between subsequent device layers with photolithographic masks. Experimental results show that the built-in stress is caused by complex atomic processes, which have been under intense study in recent years. We assume that \(\sigma_{bs}\) is constant and known, e.g., from the measurement of the curvature of the substrate. When the only stress in the film is the built-in stress, then \(\sigma_f=\sigma_{bi}\), and according to Eq. 1, the stress in the substrate is \(\sigma_s=-\sigma_{bd}/d_s\). This stress causes an elastic strain in the substrate, given by \(-\sigma_{bd}/d_s\). Here \(Y_f=Y_f/(1-\nu_f)\) is the biaxial elastic modulus, where \(\nu_f\) is Poisson’s ratio of the substrate. Consequently, at \(T_d\) after the film is deposited, the strain in the substrate is the sum of the thermal and elastic strains, namely,

\[
\varepsilon(T_d) = \alpha_s \cdot (T_d - T_r) - \frac{\sigma_{bd}}{Y_f d_s}.
\]  

After the film is deposited and the film/substrate stack has been cooled to room temperature, the stresses in the film \(\sigma_f\) and the substrate \(\sigma_s\) will assume new values. The strain in this state is denoted as \(\varepsilon(T_r)\). In the substrate, this strain is entirely due to the stress:

\[
\varepsilon(T_r) = \frac{\sigma_s}{Y_s},
\]  

In the film, the strain deviates from \(\varepsilon(T_d)\) due to the change in the temperature and the change in the stress:

\[
\varepsilon(T_r) = \varepsilon(T_d) + \alpha_f \cdot (T_r - T_d) + \frac{\sigma_f - \sigma_{bi}}{Y_f}.
\]  

Here \(Y_f= Y_f/(1-\nu_f)\) is the biaxial elastic modulus, where \(Y_f\) is Young’s modulus and \(\nu_f\) Poisson’s ratio of the film.

From Eqs. (1)–(4), one gets

\[
\sigma_f d_f + \sigma_s d_s = 0.
\]  

The substrate is stress free at room temperature before film deposition. This state is set as the reference state, in which the strain is zero, \(\varepsilon=0\). Therefore, within this entire paper, the strains \(\varepsilon\) in the substrate and the film are identical and their reference is the bare, unstressed substrate at room temperature.

Now we determine the strain \(\varepsilon\) and the stresses \(\sigma_f\) and \(\sigma_s\) after the temperature has been raised to the deposition temperature \(T_d\). The bare substrate is still stress free, but has expanded by a thermal strain \(\varepsilon=\alpha_s(T_d-T_r)\), where \(\alpha_s\) is the coefficient of thermal expansion (CTE) of the substrate.

The film grows at \(T_d\) with a built-in stress \(\sigma_{bi}\). This built-in stress is caused by complex atomic processes, which have been under intense study in recent years. We assume that \(\sigma_{bi}\) is constant and known, e.g., from the measurement of the curvature of the substrate. When the only stress in the film is the built-in stress, then \(\sigma_f=\sigma_{bi}\), and according to Eq. (1), the stress in the substrate is \(\sigma_s=-\sigma_{bd}/d_s\). This stress causes an elastic strain in the substrate, given by \(-\sigma_{bd}/d_s\). Here \(Y_f=Y_f/(1-\nu_f)\) is the biaxial elastic modulus, where \(\nu_f\) is Poisson’s ratio of the substrate. Consequently, at \(T_d\) after the film is deposited, the strain in the substrate is the sum of the thermal and elastic strains, namely,

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According to Eq. (1), the stress in the substrate is \(\sigma_s=-\sigma_{bd}/d_s\). This stress causes an elastic strain in the substrate, given by \(-\sigma_{bd}/d_s\). Here \(Y_f=Y_f/(1-\nu_f)\) is the biaxial elastic modulus, where \(\nu_f\) is Poisson’s ratio of the substrate. Consequently, at \(T_d\) after the film is deposited, the strain in the substrate is the sum of the thermal and elastic strains, namely,

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Equation (5) describes the strain of the substrate at room temperature, after film deposition as a function of film/substrate thickness ratio. The two substrates illustrated are steel with $Y_f/Y_s = 1$ and Kapton with $Y_f/Y_s = 40$, and $(\alpha_f - \alpha_t)(T_a - T_r) = 2 \times 10^{-3}$. The parameter $\sigma_{bi}/Y_f$ represents the built-in stress measured in SiN films deposited by plasma enhanced chemical vapor deposition.

$$\varepsilon(T_r) = \frac{(\alpha_f - \alpha_t) \cdot (T_a - T_r)}{1 + \frac{Y_s}{Y_f} \cdot ds/d_f} - \frac{\sigma_{bi} ds}{Y_f ds}.$$ (5)

Figure 1 depicts the strain in the substrate $\varepsilon(T_r)$ at room temperature after film deposition, calculated from Eq. (5). See Fig. 2 for numerical values of $Y$, $\alpha$, and $\nu$. The three different values of $\sigma_{bi}/Y_f$, $-2 \times 10^{-3}$, 0, and $2 \times 10^{-3}$ were chosen to match typical values of built-in stress in silicon nitride films deposited by plasma-enhanced chemical vapor deposition. The value of $2 \times 10^{-3}$ taken for $(\alpha_f - \alpha_t)(T_a - T_r)$ is approximately the mismatch thermal strain between silicon nitride deposited at 150 °C and steel or Kapton E. For the values of $\sigma_{bi}/Y_f$ used here, the steel substrate is seen to remain dimensionally stable ($\varepsilon = 0$) up to $d_f/d_s \approx 0.05$, and for Kapton up to $d_f/d_s \approx 0.001$. It is clear that dimensionally stable flexible electronics can be achieved more easily on steel substrates.

The effect of film built-in stress $\sigma_{bi}$ on substrate dimension $\varepsilon(T_r)$ is shown in Fig. 2 for 50-μm-thick foil substrates after 0.5-μm-thick silicon nitride film deposition at a temperature of 150 °C. Positive strain (tension) means that at room temperature the substrate is elongated after film growth, negative strain (compression) indicates shrinkage. [Note the opposite signs of $\sigma_f$ and $\sigma_{bi}$ in Eq. (1)] $\varepsilon(T_r)$, given by Eq. (5), is plotted as a function of the built-in stress in the film for steel [Fig. 2(a)] and Kapton E [Fig. 2(b)] substrates. As mentioned above, the film/substrate couple is held flat, as required for the alignment procedure. Because the CTE of steel and Kapton are larger than that of silicon nitride, both substrates are elongated after deposition and cooling if no built-in stress is grown into the film. The steel substrate is elongated by $\sim 20$ ppm, Kapton by $\sim 500$ ppm. When the SiN film is grown with built-in tensile stress $\varepsilon(T_r)$ is reduced. For Kapton, a built-in stress of 0.37 GPa is seen to completely compensate for the CTE mismatch between the substrate and the film, leaving the dimensions of the work piece unchanged. Therefore, by tailoring the built-in stress in the TFT layers one can keep the film/substrate couple dimensionally stable for accurate photomask overlay alignment.

A simple mechanical model for a film-on-substrate structure describes how a film deposited at an elevated temperature induces a change in the in-plane substrate dimensions. The substrate/film couple is allowed to slide freely in its plane during the film growth. When stresses develop, for example due to the built-in stress in the growing film, the resultant force vanishes. The film/substrate couple is cooled after the deposition and kept flat as a necessary condition for alignment. The substrate strain $\varepsilon(T_r)$ is calculated with respect to the stress-free, bare, substrate before the deposition. When a 0.5-μm-thick silicon nitride film is deposited at a temperature of 150 °C on 50-μm-thick steel or Kapton foil, the film causes change in the in-plane dimensions of the substrate. If the silicon nitride film is grown without built-in stress, the elongation is $\sim 20$ ppm and $\sim 500$ ppm for steel and Kapton foil, respectively. The elongation becomes smaller when the film is grown with built-in tensile stress. By tailoring the built-in stress in the film, one can design the substrate to remain dimensionally stable, thereby eliminating alignment errors.

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