The effect of coating in increasing the critical size of islands

on a compliant substrate

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A flexible electronic system may consist of a polymeric substrate and an array of stiff islands, on which devices are fabricated. When the substrate is stretched, the devices on the islands experience small strains, but the islands may debond if they exceed a critical size. We show that a thin layer of polymer coating, covering the islands and the substrate, can markedly increase the critical island size.

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In one design of flexible electronics, illustrated in Fig. 1, the substrate is a compliant polymer, while active devices are fabricated on thin-film islands of a stiff material.[1-3] When the substrate is bent or stretched, the deformation is mostly accommodated by the substrate, and the strains in the islands are small. This design readily incorporates inorganic electronic materials into flexible electronics. It has been shown, however, when the substrate is stretched by a certain amount, the islands may crack or debond when they are too large.[1,3,4] The critical size of the islands depends on materials of the substrate and the islands,[5,6] and varies statistically. Experiments have shown that the critical island size markedly increases when a coating of a compliant material is applied to cover the islands and the substrate.[3] For example, a 200 nm polymer coating enhances the survival rate of 120 μm indium-tin-oxide islands from 20% to 100%.

The object of this paper is to study how a compliant coating improves the reliability of stiff islands on a complaint substrate. We first use the commercial finite element code, ABAQUS, to analyze the stress field near the edge of an island, with or without coating. When the edge is sharp and the island is bonded to the substrate, the stress field near the edge is singular.[7,8] Our calculation shows that a coating reduces the intensity of the stress field near the edge. This result, however, does not directly translate to a prediction of the critical island size. To do so, we prescribe a failure mechanism:

debonding of the island from pre-existing flaws on the interface. We use the finite element code to compute the energy release rate of these flaws. We show that for a given fracture energy of the interface, the critical size of islands increases markedly when a coating is applied.

Consider a periodic array of islands on a substrate shown in Fig. 1. The period of the islands, S, sets the width of the unit cell in our calculation, as illustrated in the inset of Fig. 2, with a single island, width L and thickness h. In the calculation, we set $S/L = 1.5$, set the thickness of the coating to be $2h$, and set the thickness of the substrate to be $100h$. All three materials are taken to be isotropic and linear elastic, with Young's modulus E and Poisson's ratio ν prescribed for each material, and subscripts f, c and s indicating the thin-film island, the coating and the substrate. Representative Young's moduli for islands and the substrate are $E_f = 200\,\text{GPa}$ and $E_s = 5\,\text{GPa}$, respectively. In the calculation, we set $E_f / E_s = 40$, and set Poisson's ratios of all materials to be 0.3. To study the effects of coating, we will vary E_c / E_s. In practice, the island may be of a square shape, but in our calculation, to illustrate the trend and avoid three-dimensional calculations, we assume that the unit cell undergoes plane strain deformation. The two edges of the substrates are prescribed with displacement $\pm \varepsilon_0 S / 2$, and the nominal stain ε_0 will be used to represent the applied load.

Figure 2 plots the shear stress τ on the interface between the island and the substrate, distance r from the edge. The stress is normalized by $E_f^* \varepsilon_0$, where $E_f^* = E_f / (1 - \nu_f^2)$ is the plane strain modulus of the island. When $r/h \ll 1$, the relation between the stress and the distance follows a power law,

$$\tau \sim r^{-\lambda}, \tag{1}$$

as predicted in Ref. [7]. The analysis in Ref. [7] determines the exponent λ, but does not determine the magnitude of the stress. For each value of E_c / E_s, our calculation shown in Fig. 2 gives the exponent as the slope in the plot. Comparing the three cases, $E_c / E_s = 0$ (without coating), $E_c / E_s = 0.2$ and $E_c / E_s = 1$ (with a coating), we note that the coating reduces the exponent λ, and also reduces the magnitude of the stress. This effect of coating can be understood as follows. Without coating, there is an open space. When the coating is employed, the local geometry becomes a triple junction with three materials, which alleviates the elastic mismatch.

While the above calculation shows that the coating reduces the intensity of the stress near the edge, the result does not lend itself to a prediction of the critical island size. To do so, we specify a failure mechanism by introducing interfacial flaws at the edges. Figure 3 illustrates flaws, length a, placed on the interface near the edges of the island. A

dimensional analysis shows that the energy release rate of the interfacial crack takes the following form:

$$G = E_f^* \varepsilon_0^2 h \cdot F\left(\frac{a}{h}, \frac{L}{h}, \frac{E_c}{E_s}\right), \tag{2}$$

where $F\left(a/h, L/h, E_c/E_s\right)$ is a dimensionless function. Note that we have already specified a number of other dimensionless ratios, as discussed in the previous paragraphs.

The energy release rate is calculated using ABAQUS. Figure 3 plots the normalized energy release rate as a function of E_c/E_s, with a fixed flaw size $a = 0.1h$ and a fixed island size $L = 100h$. The energy release rate decreases markedly in the presence of the coating. When the modulus of the coating equals that of the island, $E_c = E_f$ (or $E_c/E_s = 40$), the coating and the island become an elastically homogeneous blanket film. In this case, the interface is free of shear and normal stresses, so that the energy release rate vanishes. On the other hand, when the coating is as stiff as the island, the strain in the middle of island will be the same as the nominal strain ε_0, so that the island will be prone to cracking. Consequently, one should select a coating compliant enough to ensure low strains inside the island, but stiff enough to alleviate the stress intensity at the edges.

Figure 4(a) plots the normalized energy release rate as a function of the normalized flaw size a/h. Three cases are considered, one without coating $E_c/E_s = 0$, the other two with compliant coatings $E_c/E_s = 0.2$ and $E_c/E_s = 1$. For example, when $a/h = 0.01$, the energy release rate reduces by 80% for $E_c/E_s = 0.2$, and reduces by 96% for $E_c/E_s = 1$. The reduction is still significant even when $a/h = 1$. For a small crack $a/h \ll 1$, on the basis of an asymptotic analysis, we expect that

$$G \propto a^{1-2\lambda}. \tag{3}$$

This scaling law is evident from the plots in Fig. 4(a). In practice, the size and the location of a flaw are statistical. The variation of the energy release rate with the flaw size may partially account for statistical variations of the critical island size observed in experiments.

The mode angle ψ is defined such that $\tan\psi$ is the ratio of the shear stress to the normal stress on the interface at a small distance ahead the tip of the interfacial crack.[9] Figure 4(b) plots the mode angle as a function of normalized crack size a/h for $E_c/E_s = 0$, 0.2 and 1. All three curves show that the shearing mode dominates.

Figure 5 plots the normalized energy release rate as a function of the normalized island size, L/h. The flaw will grow and cause debonding when the energy release rate G reaches the fracture energy of the interface, Γ. The condition $G = \Gamma$ would correspond

to a horizontal line in Fig. 5, and the intersections of the line with the curves in Fig. 5

would predict the critical island size.   Thus, Figure 5 shows the effect of the coating in

increasing the critical island size.   For example, taking representative values,

$E_f^* = 200\text{GPa}$, $h = 1\mu\text{m}$, $\varepsilon_0 = 2\%$, and $\Gamma = 10\text{J/m}^2$, we obtain that $\Gamma/\left(E_f^* \varepsilon_0^2 h\right) = 0.125$.

Drawing this value as a horizontal line in Fig. 5, we note that the critical island size is

about 24 μm in the absence of coating, and is about 90 μm with a coating of

$E_c / E_s = 0.2$.

The suppression of debonding by coating can be understood as follows. If there is

no coating, the traction-free surface of an edge is easy to move to accommodate the

deformation, so that the interfacial flaw can readily cause the island to slide relative to the

substrate. However, if a coating is applied, the displacement of the edge is constrained,

so that the crack is more difficult to propagate.

In the above discussion, we have chosen a specific failure mechanism: debonding

between the island and the substrate. The stress concentration at the edge of the island

can cause other mechanisms of failure, such as debonding between the coating and the

island, and damage of the substrate. By reducing the stress intensity near the edge, the

coating is expected to mitigate these other mechanisms as well. Quantitative analyses of

these other mechanisms are beyond the scope of this paper.

In summary, we have shown the effects of compliant coating in two ways. First, the coating reduces the intensity of stresses near the island edges by reducing the elastic mismatch. Second, the coating suppresses the delamination by constraining the sliding of dissimilar materials around the edge. Even though we study the effect of coating for flexible electronics, we expect that the coating enhances the reliability of other microelectronic devices, such as flip-chip packages.

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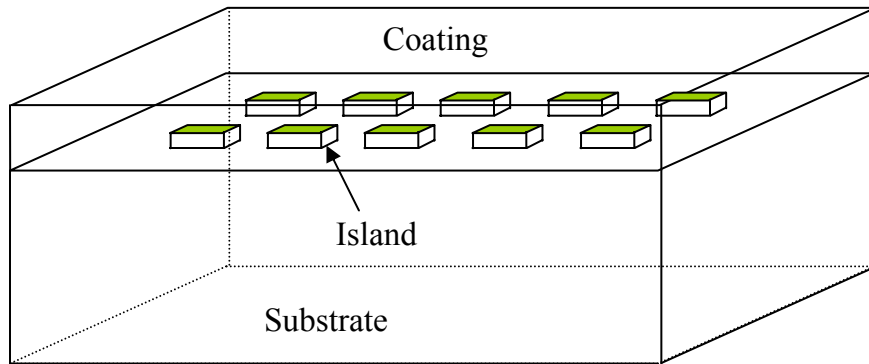9.   J. W. Hutchinson and Z. Suo, *Adv. Appl. Mech*. **29**, 63 (1992)

Figure Captions

Fig. 1. Schematic of an array of islands on a compliant substrate. A compliant coating is applied as a blanket film over the islands and substrate.
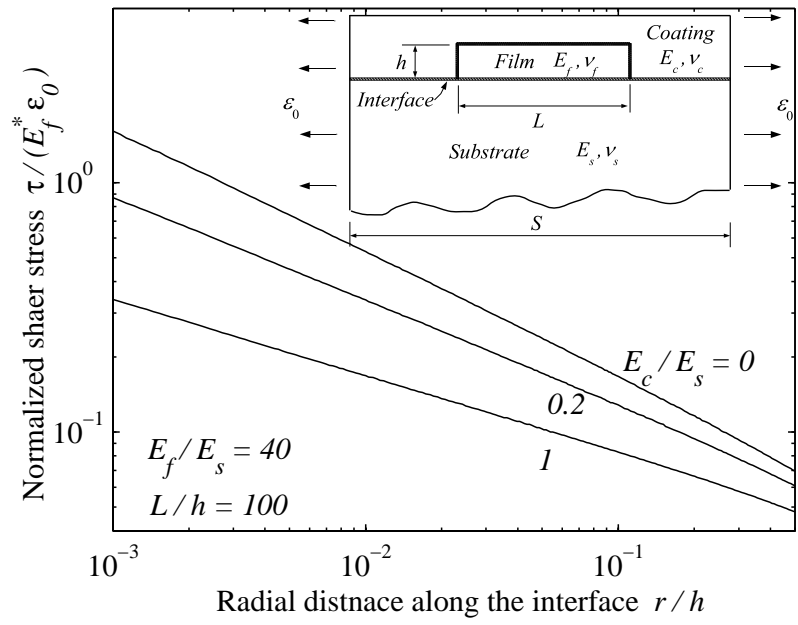
Fig. 2 The inset shows a unit cell used in calculation. Shear stress along the interface is plotted as a function of the distance from the left edge of the island. The shear stress decreases as the modulus of the coating increases.
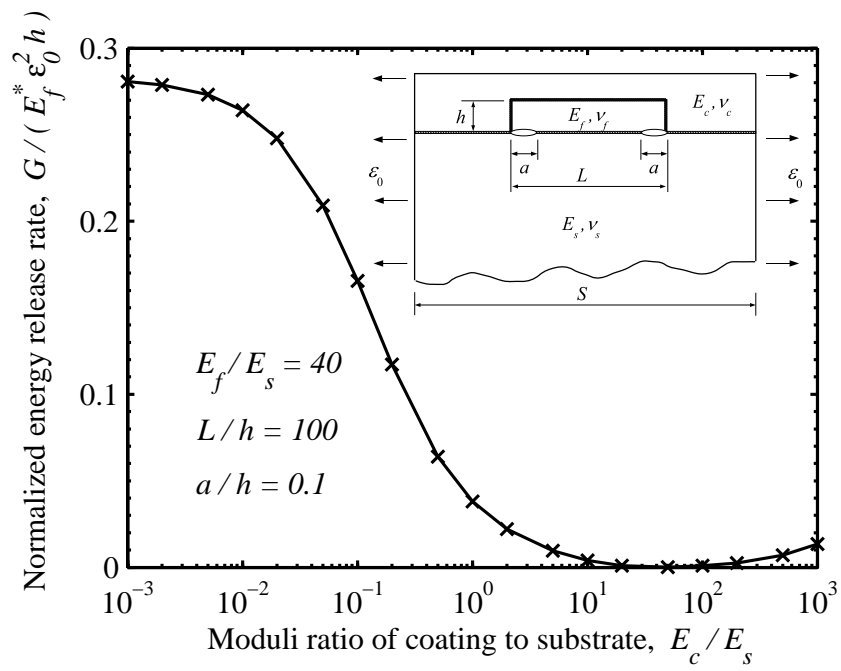
Fig. 3. The inset shows a unit cell used in the calculation. Flaws are added on the interface near the edges. The normalized energy release rate of a flaw is plotted as a function of the normalized modulus of the coating

Fig. 4. (a) Normalized energy release rate is plotted as a function of normalized crack size. (b) Mode angle ψ is plotted as a function of normalized crack size.

Fig. 5. The normalized energy release rate is plotted as a function of the normalized island size.

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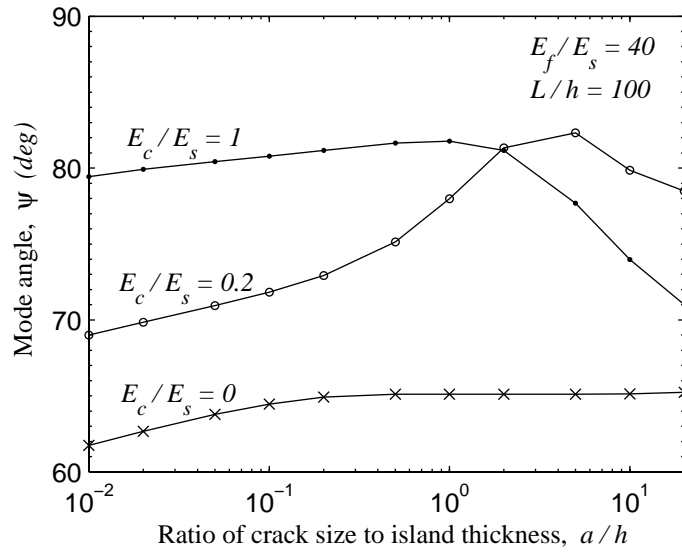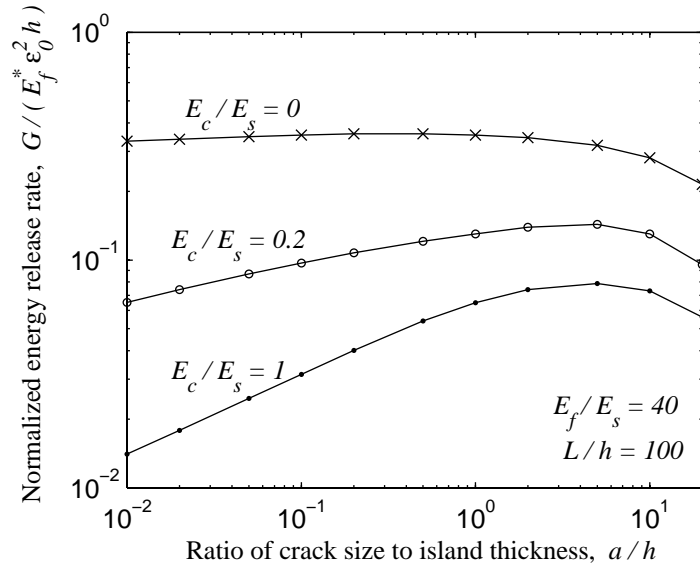
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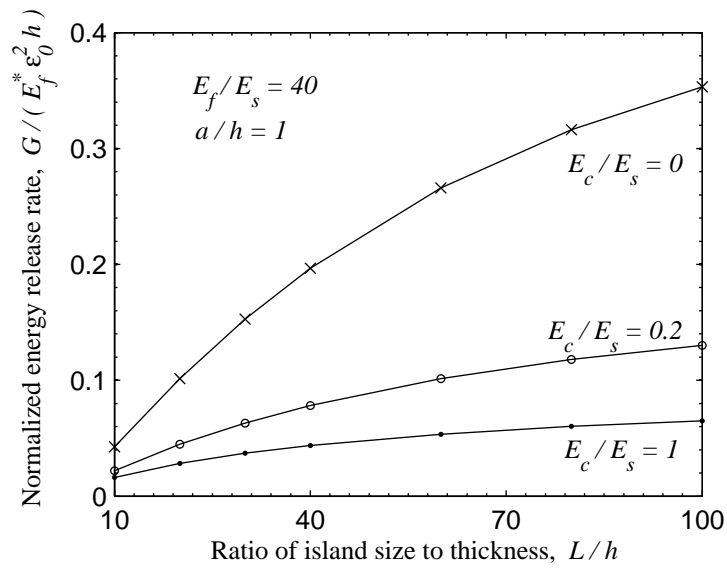
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