**Supplementary Information**

One of the concerns while building the FE model is if the substrate is thick enough. If the substrate is too thin, additional constraint to the film-substrate system would results from the displacement boundary condition applied at the bottom of the substrate, which is equivalent to using the substrate with higher modulus than the input value. To check if this constraint is avoided in our model, additional simulations are performed with the film and substrate in the FE model assigned with the same Young's modulus. In this case, the film modulus calculated from the load-displacement data obtained in FE simulation using the Oliver-Pharr model should match with the input film modulus well, as no substrate effect is expected when the film and substrate are equally stiff. The results of the check run are shown as followed in Figure S1,



FIG. S1 The film modulus is calculated by applying Oliver-Pharr model on the purely elastic film with the same Young's modulus as the substrate. Two methods are employed to obtain the contact depth: calculated using load-displacement data and measured directly from FE simulation. Both methods return film modulus close to the input value over a range of indentation ratios, which indicates that the substrate thickness is large enough to avoid over-constraint on the film.

Likewise, a convergence check is implemented for the radial dimension. The dimension of the film and substrate is extended to be *10* times of the size of the FE model we presented in the paper, with *Ef/Es=0.1 Ef/σy=50*, which is consistent with one of the cases checked in the paper. As seen in the figure below (Figure S2), no significant changes are observed in the load and displacement curve, which indicates that the radial dimension used in the paper is also sufficient.



FIG. S2 Convergence check for the radial dimension used in the FE model. The load-displacement curve from the two cases in which the radial dimension of the film and substrate set to 2000nm (the value used in the paper) and *20,000nm*, the load and displacement curve is largely overlapping with the difference of the load at *hmax (Pmax)*smaller than *1*%, it is believed that the radial dimension used in the paper is also sufficient.