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Strain-resilient electrical functionality in thin-film metal electrodes using two-dimensional interlayers

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Flexible electrodes based on metal thin films on elastomeric substrates have been ubiquitously utilized for advanced flexible and wearable electronics. However, the metal electrodes suffer from unexpected and rapid electrical disconnection after the onset of mechanical fracture across the metal film during their practical uses.

The Illinois MRSEC team has provided a readily adoptable solution of inserting an atom-thick layer within conventional metal electrodes to prevent mechanical fracture. Experiments combined with theoretical simulations reveal that 2D-interlayers modulate the in-plane fracture modes from brittle (straight) to relatively ductile (tortuous) behaviors via buckle-guided fracture mechanism. Microscale fracture behavior modulation contributes to macroscale electrical behaviors, substantially augmenting the sustainability of electrical conductance under various deformation by several orders of magnitude, which we termed ‘electrical ductility’.

Our 2D-interlayer approach can be incorporated into industrial applications of flexible, wearable electronics including foldable personal devices and further implantable bioelectrodes.

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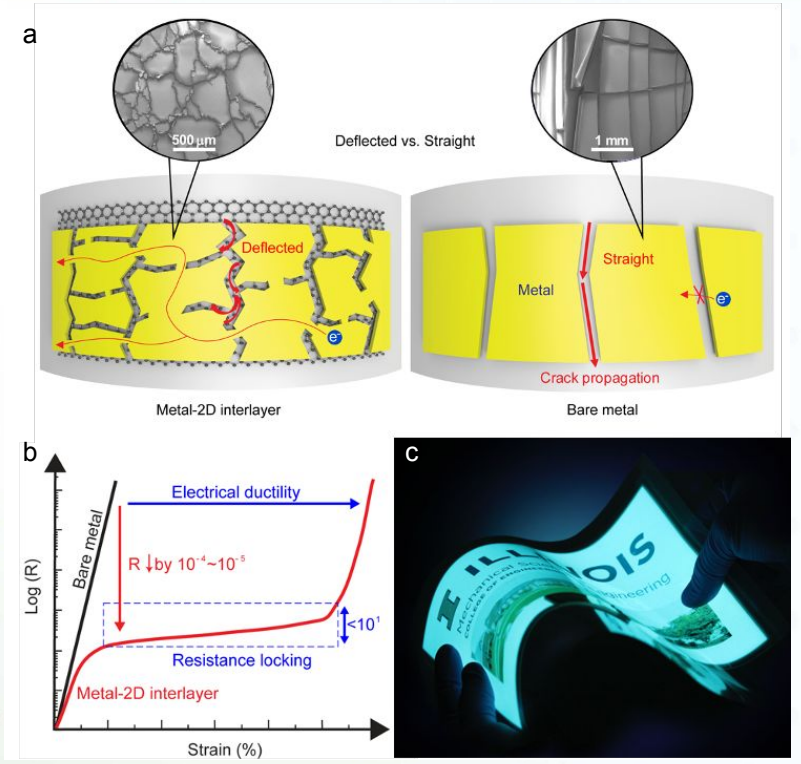

a) *Schematic illustrations (top view) of different crack propagation modes on a metal-2D interlayer electrode (left), and on a bare thin-film metal electrode (right), with scanning electron microscope images as insets.* ***b)*** *Plots of change in resistance (R) as a function of strain on bare metal (black) and on metal-2D interlayer (red) electrodes. The elongation of resistance and extended region of stable resistance with strain indicate ‘electrical ductility’.* ***c)*** *Flexible light-emitting device integrated with an electro-mechanically robust metal-2D interconnector.*

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Using electron microscopy and atomistic simulations, we probe the bending stiffness of multilayer graphene and determine their underlying bending mechanism. For monolayer graphene, we experimentally measure a bending stiffness of 1.2-1.7 eV, in agreement with theoretical calculations from our own work and from the literature. For multilayer graphene, the bending stiffness dramatically softens with increasing angle. Using atomistic simulations, we discover that multilayer graphene follows the shear-slip bending mechanism. At low bending angles, multilayer graphene behaves as a rigid body. However, as the bending angle increases, the individual atomic layers gradually shear and slip past each other, thus weakening the interlayer interactions until the multilayer graphene finally behaves as independent, frictionless layers. This transition is captured in our calculation of the scaling law of bending stiffness as a function of thickness for multilayer graphene, which gradually decays from cubic to linear above a bending angle threshold. Our work provides a unified model for bending in two-dimensional materials and show that their multilayers can be orders of magnitude softer than previously thought, among the most flexible electronic materials currently known.