Optically clear adhesives for foldable OLED displays: requirements, failure modes and solutions

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1. Introduction

Since the early 2000s, optically clear adhesives (OCAs) have been used in many applications in consumer, industrial and automotive displays. (See Figure 1.) They became the preferred bonding technology for several reasons, including superior adhesion and cohesion; they also provided superior protection and performance of touchscreens as devices transitioned from resistive to capacitive touch technology. Further, as plastic organic light-emitting display (pOLED) devices were introduced to the market, OCAs enabled new form factors, such as curved displays. They retained performance at high temperatures and humidity — key indicators of overall durability and particularly desirable attributes in mobile devices — and they could be engineered to resist yellowing after prolonged exposure to UV light.

Perhaps most importantly, OCAs offer significant benefits in display brightness and contrast. OCAs are typically based on acrylate chemistry, having a refractive index of 1.47–1.48 that is comparable to glass and other materials (e.g. polyethylene terephthalate or PET) typically found in a display device. Previously, an air gap was usually allowed between the display panel and the protective front cover; eliminating this air gap with an OCA significantly reduced the amount of light reflected at the interfaces because OCA closely matched the other materials. This, in turn, improved both contrast and brightness.

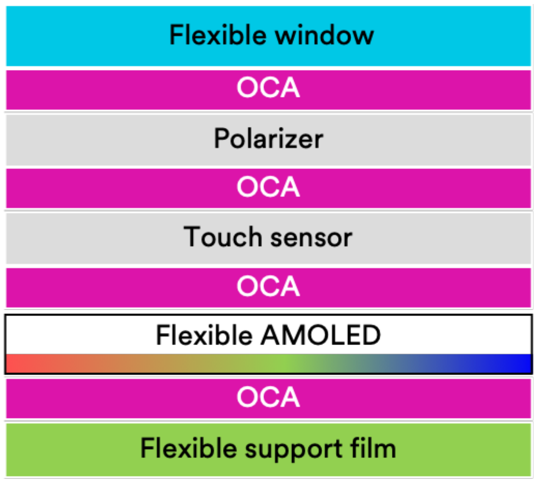


Figure 1. OCAs are used in several locations within a flexible OLED display.

OCAs are extremely versatile, providing excellent performance in both liquid crystal displays (LCDs) and OLED displays for a wide range of applications. Not surprisingly, given this versatility and performance, suppliers like 3M have created multiple OCAs for the display market. In fact, 3M alone offers more than 120 OCA options that have been tailored for specific applications in consumer, vehicle, and industrial applications — including several for foldable OLED displays.

2. Key requirements in foldable OLED displays

Foldable OLED displays, which were introduced in consumer electronics in late 2018, are a uniquely demanding application for OCAs. Obviously, these displays — and the OCAs in them — must meet conventional expectations for durability and clarity. They must also satisfy adhesion and cohesion demands — including highly specialized neutral plane[1] rheology requirements — that are unique to the display industry. Finally, they must achieve these high expectations while also being compatible with other components in the display.

For example: the OCA must retain its optical and mechanical properties for at least 100,000 dynamic folds (or approximately three to five years of average use) to a folding radius of 1-5 mm — an action that can increase the shear strain in the adhesive by more than 300 percent. It must also achieve a full and rapid recovery (again, without defects such as buckling or delamination) after remaining closed for up to 10 days (often called a static fold).

To meet these mechanical requirements, the OCA must be highly elastic (to avoid deformation). It must also demonstrate a low shear modulus (i.e., it should mechanically decouple the layers from each other in bending) but retain a high interfacial adhesion over a wide temperature range (-20 ℃ to 85 ℃), even though a low modulus typically translates to lower adhesion in pressure sensitive adhesives.

When an OCA does not reliably meet these requirements — such as when the OCA fails to shift the neutral plane near the display's electronically functional components — the display will be damaged. Typical failure modes include partial or complete fracture of the laminated stack, local or global buckling (causing delamination or a permanent deformation), creasing, and the crazing (or whitening) of the adhesive.

[1] When a film is bent, the inner surface experiences compression while the outer surface is in tension. The location within the film where these forces are in balance — i.e., where the strain is neutral — is the neutral plane. Typically, the neutral plane will be located at the midpoint of the film's thickness, but its precise location or locations in a multilayer system can be controlled through the use of OCAs.

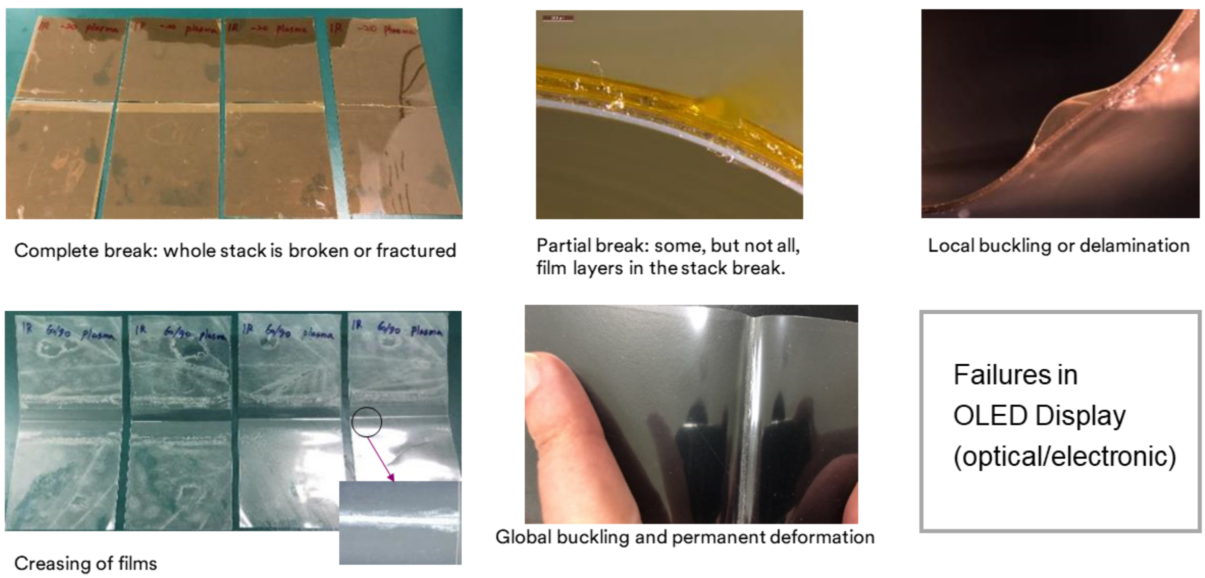


Figure 2. Failure modes in dynamic or static folding

3. Current OCAs for foldable OLEDs and the potential for customized solutions

One of the primary advantages of using acrylate chemistry for OCAs is the technology is both well understood and adaptable. The more commonly used OCAs (such as 3M™ Optically Clear Adhesive 8146) have been characterized and their performance in most applications is highly predictable. At the same time, acrylate chemistry can be customized to achieve the special requirements of foldable OLED displays.

An early such adaptation was 3M™ Contrast Enhancement Film (CEF)35, an OCA that offered low modulus, good strain recovery, and good stress decoupling along with acceptable adhesion. This profile provided excellent performance in a variety of foldable device constructions, but in certain instances device developers sought higher adhesion — particularly at high temperature. In response, 3M developed CEF36, which provided much higher addition than CEF35, albeit with a somewhat slower (but still acceptable) recovery. (See Figure 3.)

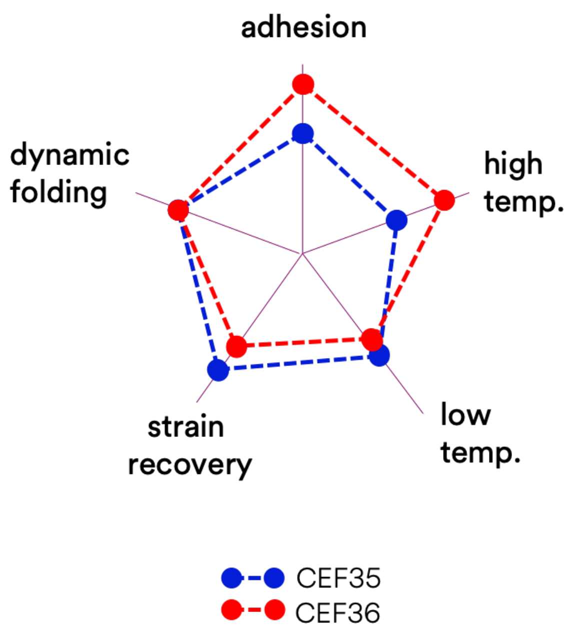


Figure 3. Modest performance differences in OCAs can make a significant difference to device designers

Obviously other customizations — addressing optical, mechanical and electronic performance — are possible with this technology; as noted earlier, 3M alone currently has over 120 OCAs for a wide range of applications.

4. Advantages of modeling new solutions

The chemistry to create a panoply of customized OCAs exists. The range and variety of potential solutions is a blessing and a curse, however. The sheer number of potential solutions suggests that designers will want a strategy to filter and pre-qualify new OCA candidates. When new candidates can be analyzed and modeled before they are fully formulated and used in prototype displays, design cycles can be shortened and development costs reduced.

Computational modeling is an especially effective tool for providing insights into the mechanical folding behavior of a multilayer film stack. Its importance derives, in part, from the limited ability of classical beam bending theory (such as the Euler–Bernoulli approach) to describe accurately the bending stress and interlaminar stress. Furthermore, the thin nature of the OLED display also makes it difficult to experimentally measure the stresses or visualize the deformation of the layers within the panel. As a result, numerical analysis methods, such as finite element analysis (FEA), offer detailed information on stress and related deformation in each layer of the film stack and allow virtual testing to evaluate different design scenarios.

Multiple design requirements can be usefully modeled, such as resistance to the impact from a drop or foreign object; for the current paper, discussion will be limited to integrity for foldability — looking first at the use of FEA for simulating the folding of a film stack and the need for material characterization tests and second at an example that details the potential failure modes of the film stack and the effects of OCA in mitigating these failure modes.

- Finite Element Analysis: The thin film nature of the film stack makes it possible to use a 2D model to represent the stack without losing much fidelity, especially when edge effects are not significant. Each layer should be modeled individually. The finite element mesh size should be sufficiently fine to resolve the stress gradient of the critical layers both in their thickness direction and in the in-plane direction, especially in the bend region where stresses vary through the thickness direction.

  The bonding of the OCA to film can be simulated by various interaction definitions such as nodal constraint or node coupling of the mesh of the OCA layer to the mesh of the substrate film layer. Typically, this approach will not allow the complex simulation of the separation or debonding of the OCA from the substrates; however, it can offer most of the needed information to evaluate the bond performance without added complexity. (If simulating the debonding process, cohesive elements may be used to represent the OCA bond; in such instances, special care should be taken to incorporate the cohesive law that describes the debonding force-displacement of the OCA bond attached to the specific films of the actual application. In general, the correct application of cohesive elements or cohesive contact for OCAs is complex. Proper training on the technique is necessary to avoid misrepresentation of OCA bonds.[2])

- Material characterization tests: Before using FEA to model an OCA/film stack, data are needed to calibrate the models. For calibrating elastic or hyperelastic material models, one or more of the tests listed below needs to be performed on the OCA:

  - Uniaxial tensile
  - Simple shear
  - Biaxial tensile
  - Compression and/or bulk compression

  For viscoelastic model calibration, dynamic mechanical analysis (DMA) tests can produce master curves of the storage modulus and loss modulus of the OCA. Otherwise, relaxation or creep test data at various strain rates and temperatures of interest may be used. For calibration of OCA bond strength models, such as the cohesive zone model, proper measurements of the bond strength using T-joint specimens and lap shear specimens are necessary. These tests should be performed on the actual substrate materials of the film stack, especially if the potential failure mode may be adhesion failure.

- Modeling an OCA using FEA: Being a type of pressure sensitive adhesive, the OCA needs to be soft enough to flow under application of pressure to wet the substrate. This intimate contact between the OCA and the substrate allows molecular interactions such as van der Waals forces to form the basis of the adhesion that underwrites the overall bond strength. This flow-like behavior of OCA can be described by a combination of nonlinear elastic and viscoelastic/viscoplastic material models.

[2] It is recommended that interested parties consult with 3M technical support for test methods, material characterization or test data related to bond strength simulation.

For the OCA's viscoelastic behavior, its relaxation function can be defined in terms of a series of exponentials known as the Prony series. For the nonlinear elastic or hyperelastic constitutive models, polynomial hyperelastic models are most commonly used. They include the neo-Hookean model, Mooney-Rivlin model, and Yeoh model. All are effective in describing an OCA's ability to stretch to very large strain. Other hyperelastic models including Arruda-Boyce and Ogden models may also be used. The commercial FEA packages, such as ABAQUS, ANSYS, and COMSOL offer finite strain computational methods and material model libraries that allow advanced simulation of OCAs. Users can apply the material model calibration tools provided by the FEA software packages to evaluate the material parameters for these constitutive models from OCA material characterization test data.

5. FEA modeling: an example

In the FEA model presented here, a simplified 7-layer film stack was used to represent a foldable OLED display. The film stack was assumed to be attached to two rigid back plates joined by hinges with two pivot points near the central bend section (two-axis folding motion). The center portion of the film stack was not attached to the rigid back plates to allow for folding of the stack. The folding action simulated here is so-called "out-folding": the film stack is folded towards its back layer. In the fully folded configuration, the space between the straight sections of the outer layer is 10 mm resulting in the bend section of the film stack forming an approximate semi-circle of radius 5 mm as shown in Figure 4.

In the simulation, the film stack was folded in three seconds, then held in the folded shape for 24 hours before it was unfolded. The material properties and the thickness of each layer used in this work are listed in Table 1. The total thickness of the film stack simulated here was 0.475 mm (layup 1) and 0.275 mm (layup 2). The simulation was repeated for these two layups bonded either by 3M Foldable OCA CEF3501 or by 3M OCA 8211, both 25 microns thick. 3M CEF35 has a lower storage modulus than that of 3M OCA 8211 and exhibits a more elastic behavior as indicated by its lower tan(delta) value (Table 1) than that of 3M OCA 8211.

The simulation was performed using the ABAQUS finite element analysis package. Due to the large ratio of film stack width to thickness, a two-dimensional plane strain model meshed with the plane strain solid element was used. Six elements were used through the thickness for the OCA layer, and four elements through the thickness for each of the other functional layers.

Layers	Thickness (µm)	Material	Modulus of elasticity, *E*, (GPa)	Storage Modulus, *G'*, (GPa) at frequency of 1 rad/s	Tan (delta)
Cover film	150 (50)	PET	3.5	NA*	NA
OCA	25	3M™ CEF3501 (3M™ OCA 8211)	/	0.03E-3 0.07E-3	0.33 0.70
Circular polarizer	75 (125)	Triacetyl cellulose	3.2	NA	NA
OCA	25	3M CEF3501 (3M OCA 8211)	/	0.03E-3 0.07E-3	0.33 0.70
AMOLED	75	Polyimide	3.5	NA	NA
OCA	25	3M CEF3501 (3M OCA 8211)	/	0.03E-3 0.07E-3	0.33 0.70
Back plate	100 (150)	PET	2.7	NA	NA

*NA = Not Applicable
The thicknesses shown in parentheses are the values used for stack layup 2.

Table 1. The simplified 7-layer film stack layup and the properties used in the simulation (all at room temperature)

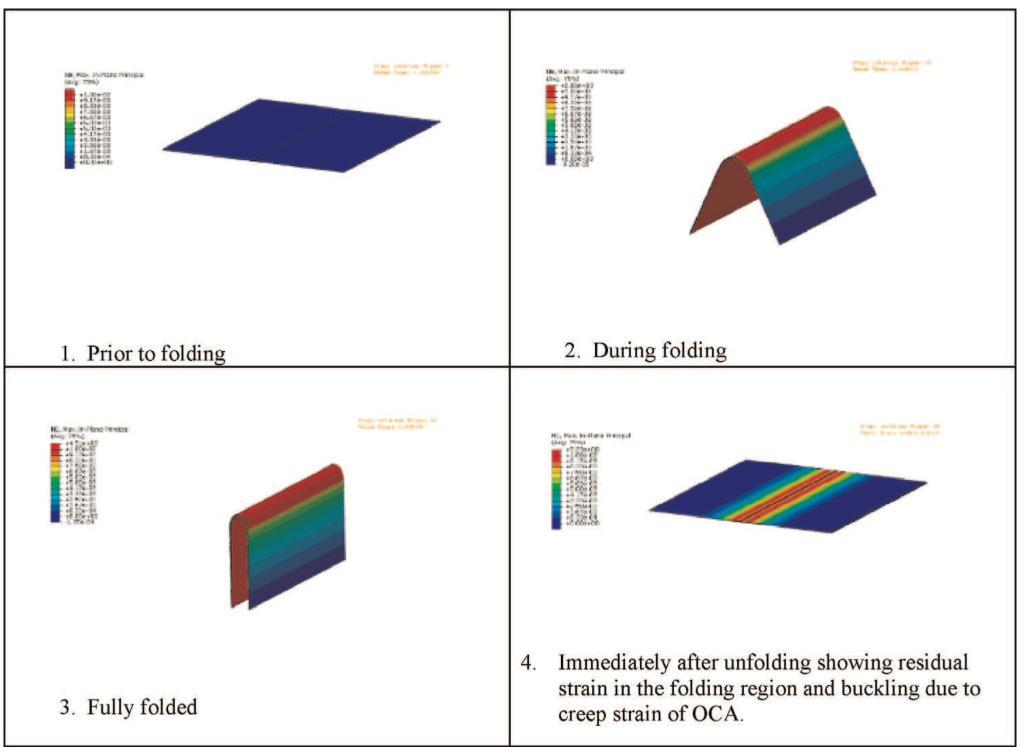
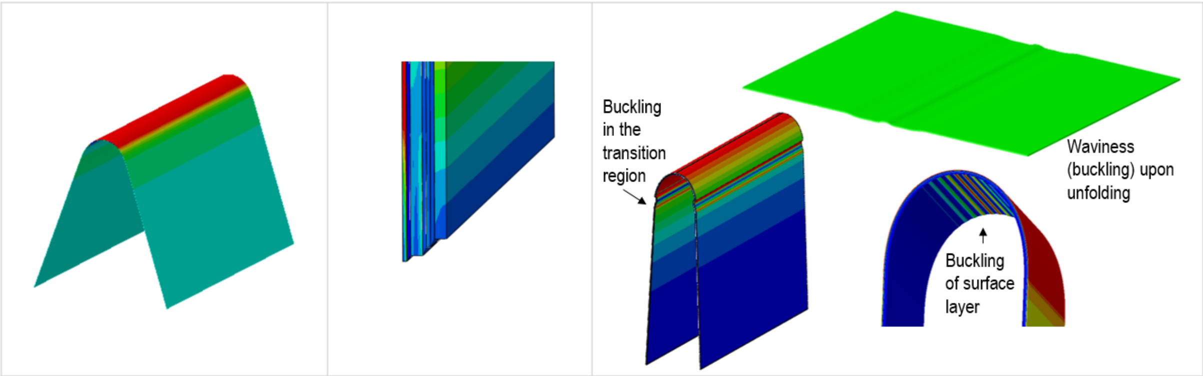


Figure 4. Simulation results showing the 4 stages of folding.
The film stack is folded away from its cover layer — so-called "out-folding"

This and other simulations of folding OLED display film stacks demonstrate OCAs' abilities to reduce bending stresses and to create multiple neutral planes in a film stack. They also demonstrate three key potential failure modes for displays under dynamic folding and unfolding (Figure 5).

- Film fracture due to high tensile bending stress
- Buckling (local buckling of a few layers in the film stack, or global buckling where the entire film stack assumes a wavy form)
- Delamination or debonding of adhesive



Fracture due to tensile bending stress | **Shear and debonding at the end of film stack** | **Buckling – local and global buckling**

Figure 5. Important potential failure modes of foldable display film stack

These failures can be addressed through the design and use of appropriate OCAs — but the appropriate OCAs on their own are not sufficient. The folding performance of a display is governed by the properties of each layer in the stack as well as the display attachment methods and folding hinge design. Nevertheless, as the softest layers in the film stack, the OCAs play a critical role in optimizing the film stack's folding performance by adjusting neutral plane location(s). This is especially true when the options to alter the mechanical properties or thickness of other functional layers are constrained. Design of display systems that utilize OCAs' unique characteristics can increase robustness of integrated foldable displays.

6. Importance of physical testing

As demonstrated above, modeling provides an efficient and economical method for conceptualizing and pre-qualifying new OCA candidates from among the large range of potential solutions. While a necessary step in product design, modeling is not sufficient. Physical testing is a next step to supplement and confirm information derived from modeling.

In particular, it is useful to evaluate the adhesive and cohesive properties of a candidate OCA through physical testing of tensile, compressive, and shear loading; tools include mechanical load frames, rheometers, and texture analyzers. These data also feed and calibrate the adhesive material model in FEA.

3M also designed and built a bend tester specifically to assess OCAs' performance in a foldable OLED device. Samples are mounted to the bend tester and folded to a specific bend radius and number of bend cycles at a defined rate (bend cycles per minute). Materials can fail by yielding, breaking, and/or buckling during testing.

Working with this and other best test systems, 3M has developed a controlled and repeatable folding test that minimizes bending stress on foldable test specimens and demonstrates the types of folding defects observed in single and multi-layer polymeric stacks consisting of OCA and ITO (indium tin oxide)-coated PET.[3]

A full discussion of this folding test is beyond the scope of this introductory paper; nevertheless, a few key features:

- It relies on a dual-pivot testing apparatus, which can prevent added strain or stretching of the samples during folding.
- Specimens are usually attached to the test apparatus using adhesive instead of clamping. (If specimens are attached to the folding test apparatus with clamps, additional stress is introduced.)
- The attachment location is no closer than 3*g/2, where g is the distance between confining test plates and attachment adhesive. The central bend region of the specimens is not attached and is free to fold.
- Rigorous attention is paid to the correct alignment of the test specimen. Misalignment can result from an off-centered attachment of the test specimen, misaligned pivot points (non-parallel or collinear), or curved/warped mounting plates. This increases variability in the test responses.
- Specimens are conditioned at well-defined environmental parameters prior to testing; testing takes place in a controlled temperature and humidity environment.
- This test regimen can reveal a range of defects and failure modes, including: crazing; breakage; local buckling caused by adhesion failure between layers; and global buckling caused by elastic instability, which inverts the fold of the test specimen.

3M has also developed protocols for testing the performance of 3M's foldable OCAs. For one such protocol, a thin layer of ITO was coated onto 2mil PET. The ITO-coated PET was laminated on both sides of an OCA, either standard OCA 8146–2 or CEF3502 (2 mils), to create 3-layer specimens. The test specimens were folded, with ITO on the out-folded/tension side, using a dual-pivot bend tester at 30 cycles per minute, with nominal folded gap of 4 mm (radius = 2 mm). Samples were conditioned for 24 hours and tested at 23 °C, 50%RH. Electrical resistance of the ITO coating was measured at the end locations of each test specimen (using an Ohm meter) after 0, 1, 10, 100, 1000, and 10,000 fold cycles.

[3] This test adheres to the International Electrotechnical Commission folding display test protocol (IEC62715–6-2:2017); 3M was a major contributor to this and other sections of the protocol.

Stacks constructed with CEF35 showed significantly less resistance increase than those containing OCA 8146–2, proving experimentally that CEF35 more effectively decouples the polymer film layers, due to a lower shear modulus, decreasing damage to the conductive layer.

These tests are useful in their own right (i.e., in their results regarding individual OCAs) and as illustrations of how well-designed physical testing can reveal important performance characteristics of candidate OCAs before the construction of prototype devices.

7. Summary and future requirements for OCAs for foldable OLEDs

Foldable OLED displays present unique challenges for bonding. In addition to the classic expectations for OCA clarity and optics, foldable displays have unique neutral plane rheology requirements and demand atypical adhesion performance. Finally, bonding solutions must be mechanically and electronically compatible with other elements in the film stack.

OCAs based on acrylate chemistry are both well-characterized and adaptable. Current OCAs have a wide range of mechanical properties, and new, customized solutions can certainly be developed. This wide range of possible solutions is attractive, but it also highlights the importance of modeling, testing and analysis — ideally before investing time and resources in the development of a prototype. Tools and protocols for such modeling, testing and analysis currently exist and will evolve over time.

The demands on OCAs from current flexible display designs are nontrivial, and they will almost certainly become more significant in the future. Some of these demands can be predicted with confidence.

- Through the next decade, manufacturers will push for narrower folding/rolling radii, multiple folding axes in displays, and longer device lifetimes, especially in terms of cycles of flexing. As folding radius decreases below 3 mm, the required adhesive shear strain will likely increase from 300 percent to 700 percent — and possibly even more. Additional folding axes increase the total magnitude of shear displacement, as each axis adds its own displacement to the system. Rolling devices will initially launch with radii of several centimeters, which is larger than today's one-axis folding displays, but the shear will add up with each bend such that the "creep" with applied stress will be a more critical property. With larger creep, even a flexible adhesive could shear out several mm at the edge when the display is rolled, resulting in unsightly uneven edges; in the worst case, display layers could press into the bezel/frame bonding and generate further stress.

- Thinner display modules will assist flexibility, so trends in integrating functional components are likely to continue. These may include coated circular polarizers or color filters integrated with the OLED encapsulation. With thin flexible cover windows (CWs), adhesives on either side of the OLED display should play a greater role in protecting the module from impact damage. This will be especially true for plastic cover windows compared to glass, since they have lower elastic moduli.

- Plastic cover windows will likely experience further growth in automotive displays, in part out of safety concerns; manufacturers are concerned about the possibility of glass display covers shattering in an impact or crash. High-performance plastic CWs are often made of PC or PMMA, so durable bonding to these low surface energy plastics, with their tendency to release gases under heating, will be important to future automotive OCAs. Additionally, ergonomic and aesthetic considerations will lead to the proliferation of larger displays with complex curves in vehicles.

- Finally, cameras and sensors will continue to be integrated in displays. In a video telephone application, for example, locating the camera behind the screen allows a more natural interaction; the camera may track a user's gaze at the same location where the user views the other person's face, giving the impression of eye contact. Currently, many sensors and cameras can fit in a droplet shape or notch cut of out of the active display area (including OCAs) at one edge of the screen. When the camera(s) are behind the display, some adhesive layers must precisely maintain a small hole in the middle of the part(s) as an aperture for the camera. This implies that future OCA bonding will be required to satisfy stricter dimensional controls and tolerances.

These new expectations will challenge the designers and manufacturers of devices and the components within them. The increasing complexity of these devices also reinforces the importance of collaboration among all parties, to ensure that bonding solutions and other components in the display and electronic device are mechanically, optically, and electronically compatible — or even synergistic to unlock further capabilities.