







Song Jiaqi Et Al.'s work describes flexible InGaZnO thin-film transistors (TFTs) and the recent advances in their development. The paper introduces flexible InGaZnO TFTs and their superiority over rigid counterparts. The fabrication process of these TFTs is explained, along with the recent advances in their electrical performance and mechanical flexibility. The paper also discusses the mechanisms behind the bending-induced instability. [31]

Prevatte Carl Et Al.'s work aimed to describe a framework for manufacturing versatile, high-performance displays using a hierarchical assembly strategy. [32]

Ke Tsung-Ying Et Al.'s work describes the method of separating flexible electronics from a rigid carrier glass for flexible OLED display production. The method involves using a weak bonding method and mechanical de-bonding with a protection film assistance. The paper also demonstrates the advantages of not using a PI substrate in flexible OLED display production. [33]

María Rodríguez Fernández Et Al.'s work aimed to help us understand primary display production technology especially those with minimal power consumption. Energy usage of these displays was observed. Even though significant progress has already been accomplished in this area, industry strategy objectives and research group lines of inquiry still have this goal as their primary purpose. [34]

Danny Ziyang Huang Et Al.'s work describes the history and characteristics of folding mobile phones before elaborating on their effects on human society. The paper came with observations that People strive for the highest level when people and technology are combined. Life is altered by technology. Both the engineering and the user interface of the folding screen phone carrier are first-rate. [35]

Shanshan Wang Et Al.'s work aimed to investigate and contrast the current research on picture retargeting in order to suggest an improved integrated content-aware image retargeting system that outperforms competing ideas. The paper's important topics, which should contain items and their surroundings, are the main emphasis of the essay. An importance map is used in an image retargeting system to express the significance of specific pixels within the image. [36]

Li-Wei Kang Et Al.'s work aimed to describe probable causes for image distortion on foldable displays. A portion of a displayed image on a mobile device may be squished when the device is folded to a specific extent. [37]

Peng Fei Bai Et Al.'s work helps us understand multiple paper-like technologies with a focus on the current state and potential trends in the future. It was observed that the driving waveform was essential to the electrophoretic display and it greatly affected various aspects such as refresh rate, image quality, flicker, etc. Continued advancement of electrofluidic display technology may be a promising option for displaying video in a manner akin to paper. [38]

Zhiyuan Zhao Et Al.'s work discusses various advancements in display technology from thick electronic tube technology. It was observed that flexible displays have certain distinct advantages over traditional rigid displays,

like being lightweight, having an ultrathin construction, consuming less energy, and having a higher mechanical deformation tolerance. [39]

Kim Do-yoon Et AL.'s work conveys the fact that displays are essential for conveying visual data and information across various media platforms. Reflective displays, which differ from emissive displays in certain ways, are becoming more prevalent among screens. In order to create flexible reflective displays, we have examined a number of fabrication methods. Every component of the flexible display should be replaced with stretchable material for optimal performance. The creation of stretchy materials and reflecting screens, however, has undoubtedly made some small but significant strides. [40]

### 3. Background

This section of the paper mainly focuses on the history of the flat phones, the problems it ran into over the years along with an added insight into curved displays and foldable phones.

The concept of flat, or “slate” smartphones started with the introduction of the Apple’s iPhone by the cofounder of Apple Steve Jobs in 2007. The Apple iPhone initiated the trend of flat smartphones with the introduction of a touch-screen device which can execute multiple instructions just like a computer. Other firms also followed suit, and then launched their own versions of smartphones, each with unique features, which then resulted in the widespread popularity and acceptance of the flat phones. Over the years, there have been numerous developments to these flat phones, making them powerful, slim, and containing loads of features. Now, even though the flat phones are quite popular these days, they do come with their own sets of problems. Flat phones have several shortcomings which include difficulty in handling mainly because of the size, glare and reflections on the screen, and limited viewing angles.

The introduction of curved displays surely did create a lot of “buzz” in the technological sector, with Samsung being one of the first companies to introduce curved displays. After Samsung, a lot of companies such as Realme, Google, OnePlus, Vivo, Xiaomi and many others followed suit to take a chunk of the market share. In recent years, these curved displays have gained popularity, with the most premium phones having the curved design. There are more benefits than which meets the eye. These smartphones include enhanced aesthetics, improved grip and better handling, along with ease of typing and pressing buttons. Research also shows that there is a reduction of screen reflections as well as the glare to the human eye. Not to mention, these phones have a very eye-catching look. The curved part of the display helps in giving the user a more immersive experience while streaming High Definition (HD) videos and video games. These phones, however good they are, have their set of limitations. These include a high price point, Reduced Screen Area, and Image Distortion because of the curvature of the edges.

But, despite these challenges, these curved displays continue to maintain their popularity in the smartphone market, mainly due to the benefits they offer when it comes to aesthetics, handling, comfort and grip.

The next turning point in the Technological Sector was the introduction of the foldable phones. The Selling point of these phones is evident in the name, i.e., phones which could be folded into a smaller device when compared to the original device. These phones could be smaller than the typical phones which exist these days in the market. These phones can transform into a large tablet-like form factor when needed. This allows the user to take advantage of a larger screen for multiple tasks such as gaming, streaming HD videos and movies while retaining the simplicity and the form factor of a smartphone. The first commercially available foldable phone was the Samsung Galaxy Fold, which was released in 2019. Since Samsung's launch, many other companies followed suit such as Microsoft, Xiaomi, Oppo, Motorola among many others. The launch of foldable phones was met with a lot of excitement and skepticism, mainly because of its underlying technology still being in the early stages as well as the challenges that lie ahead of it. One of the biggest advantages associated with the foldable displays is that with a foldable device, you have twice the space in the underlying hardware, so it's possible that you could have a battery with more capacity or even a more powerful processor. Where normal phones usually have a camera island at the back and then a separate selfie camera at the front of the phone, this is not necessary with the foldable displays. This gives manufacturers the opportunity to pay more attention to just that camera island. Even though the foldable displays enjoyed a lot of attention, they had their own set of limitations with them. Some customers found the phone very thick and tougher to handle. One of the major question marks for the companies were to include a single Operating System (OS), or a dual Operating System (OS). The Hinge mechanism that allowed the phone to fold and unfold was very prone to wear and tear over time, and this affected the longevity and reliability of the phone. These phones were usually very expensive to own, and very few in a number, and hence, they were not widely available in the phone markets.

But, despite these drawbacks, these foldable phones are seen as a new and an interesting development in the phone industry, and they are expected to gain more popularity and users over the years as the technology progresses and improves.

#### 4. Technology behind the Curved displays and advantages compared to flat phones

Living in the digital era, we have all heard about the concept of curved displays, but seldom do we know about the technology behind creating these curved displays. This section of the paper will discuss exactly that, so the readers will have a better understanding of how curved displays are manufactured. The technology behind curved displays

involves the use of flexible display panels, such as OLED (Organic Light Emitting Diode) or LCD (Liquid Crystal Display). These can be bent into a curved shape. These panels are made up of different layers of multiple light-emitting diodes or liquid crystals that are sandwiched between two pieces of glass. The bending of the panel is achieved by mounting it on a flexible substrate, such as a plastic or metal frame. Now, the curvature of the display panel can then be tailored according to one's specific requirements, which allows for a customized viewing experience.

Curved displays offer many more competitive advantages than the traditional flat displays, which also includes a more immersive viewing experience attributed to a wider field of view, and reduced reflections and glare due to the curvature of the panel. Research also shows that because of the curvature of the display, eye strain as well as fatigue can be reduced by providing a more uniform viewing distance to the eyes, along with a more aesthetically pleasing appearance. Curved Displays are also known to be easier to handle compared with the flat phones providing a comfortable grip.

#### 5. Technology behind Foldable Displays and advantages compared to Flat phones

There are various technologies that are used by foldable displays to achieve the best performance and ease of use. As foldable displays are supposed to "fold", various issues such as creasing, breaking, discolouration and many more arise. One way to increase foldability is by using a fan-out daisy-chain linked packaging style. This was originally used for CMOS dyes on an elastomeric substrate. As large thinned dyes were prone to degradation on bending, multiple smaller dyes were linked together in a fan structure to enable safe bending. This can be applied effectively to OLED and micro-LED displays. Recently with the introduction of other substrates such as plastic, UTG (Ultra-thin glass), metal, etc. foldable displays are becoming more and more of a reality. Ultra-thin glass can be a suitable substitute for the cover window of the display. It is hard and more flexible than glass (does not break or crease even at a bending radius of  $1.5R$  and is reliable against cracks). Another technology that can be used to laminate the bendable cover window on a foldable display is to use a multi-hardness silicone pad. Conventionally, the cover window is laminated with OCA (Optically Clear Adhesive) but it has been found to cause degradation of the display panel due to the technology used in the lamination process. This method of using a hybrid silicone pad has shown to have excellent compression strength and uniformity without causing any degradation. Apart from the physical integrity of the cover window and substrate, the wiring in the conducting layer can also be optimized by using suitable routing schemes. This ensures that the wiring in the layer does not suffer from degradation. There are also recent improvements in the manufacturing process of the

thin glass to be used in the display also. Conventional methods require the use of chemicals and grinding thick glass down to the required thickness. A novel green method has been proposed that employs a bonding and separation method to create thin glass of optimal thickness.

The above-mentioned technologies are just a fraction of many more innovative technologies and approaches to make foldable displays reliable and easier to use.

## 6. Technical Challenges associated with curved displays and suggestions on overcoming them

This section discusses primarily about the different technical challenges associated with the curved displays, and it will also suggest ways we can overcome these challenges for effective utilization. Some of the Technological Challenges include:

1. **Display Flexibility:** A Flexible substrate is needed in order to build the curved shape of the display, which is not the easiest task when it comes to manufacturing.
2. **Mechanical Strength of the Phone:** The curved shape of the display makes the phone more fragile and hence more prone to damage.
3. **Touch Sensitivity:** The touchscreen technology may not work as effectively on the curved displays, which leads to difficulties in touch accuracy.

There are ways in which we can overcome the above challenges. Display Flexibility of the curved screens can be increased with the help of flexible substrate materials, such as either plastic or flexible glass. Research has been ongoing into flexible materials such as graphene which reduces the risk of damage during manufacturing and use and hence thereby increasing the display flexibility.

The most common way to increase the mechanical strength of the curved display is to use a tempered glass, but other than that there are many ways to go about increasing the mechanical strength of the displays. Lamination of the display with stiffening materials, such as Polymer films or metal layers will reduce the risk of damage by a significant amount and hence even increase its Mechanical Strength. Even the use of high-strength substrate materials will help increase the mechanical strength of the curved displays. When it comes to the touch sensitivity, we could use improved touch sensors which will have better accuracy. These improved touch sensors will be able to detect with good accuracy if the touch is accidental or not. We could use multiple touch sensors around the curved displays as well to improve touch accuracy and address touch sensitivity issues.

## 7. Technical Challenges associated with Foldable displays and suggestions on overcoming them

There are a few technical challenges associated with foldable displays as well, which is precisely what the section covers. The section will also cover sound strategies on addressing these issues. Some of the problems faced by the foldable displays include:

1. **Integration with Hardware:** Integration of the foldable display with other hardware components such as the battery, storage and the processor can be a very difficult task. It must be done very carefully in order to ensure high performance and reliability.
2. **Touch Screen Accuracy:** Touch screen might not work that effectively in foldable phones, which reduces the accuracy of these touches.
3. **Software Optimization:** The foldable phones require software optimization to ensure a seamless as well as a consistent User Experience, particularly when the device is folded and unfolded time and again.

There are a few ways in which we could overcome these above challenges in order to enjoy the benefits of the foldable phones. To avoid the Hardware Integration issues, manufacturers need to take care of multiple things such as the Hinge design, which was discussed earlier in the paper. The hinge mechanism of the foldable phone should be able to endure the frequent opening and closing of the device, as well as should ensure that unwanted materials such as dust and debris do not enter. We could as well use flexible materials for manufacturing the foldable phones which would be resistant to scratches and cracks. We could improve the touch screen accuracy by integrating the phone with a high-resolution display. This allows for smaller touch points on the screen. We could as well reduce the display thickness of the phone, as it would have a major impact on the touch accuracy of the phone, as these thicker displays have trouble recognizing inputs from the user

When it comes to software optimization of the phone, we could collaborate with different software developers, to ensure that the software which is running on the foldable display is optimized or not for the underlying hardware. Managers should also test the software as thoroughly as possible on the prototypes of foldable phones, which will help to identify and fix any issues that might affect its performance, reliability or touch accuracy.

## 8. Conclusion

This survey study paper has examined the emergence of curved and foldable displays as well as their prospective market impact. Both technologies have the potential to completely change how we use our gadgets and create new user experience possibilities. Foldable displays have the



advantage of having more screen space in a portable design, which might make multitasking more effective and fun. Moreover, new use cases and applications might be created as a result of foldable displays. Apart from potentially reducing screen glare and offering a broader field of view, curved screens offer a more immersive viewing experience. This might be very helpful in virtual reality and gaming applications. In the future, the adoption of these technologies will be determined by a variety of factors, including cost, durability, and consumer demand. However, as manufacturers and developers seek to differentiate themselves in an increasingly crowded market, we can expect to see continued innovation and development in both areas.

Overall, foldable, and curved displays are exciting developments in display technology that have the potential to improve how we interact with our devices and consume content. It will be interesting to see how these technologies are adopted and integrated into our daily lives as they continue to mature.

## References

- [1] Yi J, Park S, Im J, Jeon S, Kyung G. Effects of display curvature and hand length on smartphone usability. In Proceedings of the Human Factors and Ergonomics Society Annual Meeting 2017 Sep (Vol. 61, No. 1, pp. 1054-1057). Sage CA: Los Angeles, CA: SAGE Publications.
- [2] Lee Y, Lee JH, Kim YM, Lee J, Kwon S, Sim H, Yun MH. The Effects of Curvature of Edge Screen on Subjective Feelings in Smartphone Usage. In Proceedings of the Human Factors and Ergonomics Society Annual Meeting 2017 Sep (Vol. 61, No. 1, pp. 1269-1270). Sage CA: Los Angeles, CA: SAGE Publications.
- [3] Park J, Heo S, Park K, Song MH, Kim JY, Kyung G, Ruoff RS, Park JU, Bien F. Research on flexible display at Ulsan National Institute of Science and Technology. npj Flexible Electronics. 2017 Nov 13;1(1):9.
- [4] Ashish Kumar Mishra "Foldable World" Published in International Journal of Trend in Scientific Research and Development (ijtsrd), ISSN: 2456-6470, Volume-4 | Issue-4, June 2020, pp.1604-1607, URL: <https://www.ijtsrd.com/papers/ijtsrd31616.pdf>
- [5] Lee Y, Kim W, Lee JH, Kim YM, Yun MH. Understanding the relationship between user's subjective feeling and the degree of side curvature in a smartphone. Applied Sciences. 2020 May 10;10(9):3320.
- [6] Huitema E. The future of displays is foldable. Information Display. 2012 Feb;28(2-3):6-10.
- [7] Alam A, Hanna A, Irwin R, Ezhilarasu G, Boo H, Hu Y, Wong CW, Fisher TS, Iyer SS. Heterogeneous integration of a fan-out wafer-level packaging based foldable display on elastomeric substrate. In 2019 IEEE 69th Electronic Components and Technology Conference (ECTC) 2019 May 28 (pp. 277-282). IEEE.
- [8] Ha MH, Choi JK, Park BM, Han KY. Highly flexible cover window using ultra-thin glass for foldable displays. Journal of Mechanical Science and Technology. 2021 Feb;35:661-8.
- [9] Sun N, Jiang C, Li Q, Tan D, Bi S, Song J. Performance of OLED under mechanical strain: a review. Journal of Materials Science: Materials in Electronics. 2020 Dec;31:20688-729.
- [10] Jang DH, Han KY. Multi-hardness hybrid silicone pad to laminate the bended cover window in a flexible OLED display. Journal of Mechanical Science and Technology. 2021 May;35:1987-92.
- [11] Ma L, Gu J. Optimized Design of Wiring Scheme for Conductive Layer in Bending Area of a Flexible OLED. Russian Physics Journal. 2021 Jul;64:450-62.
- [12] Lee SM, Shin D, Yun I. Degradation mechanisms of amorphous InGaZnO thin-film transistors used in foldable displays by dynamic mechanical stress. IEEE Transactions on Electron Devices. 2016 Dec 5;64(1):170-5.
- [13] Chen JT, Yang SH. Novel green temporary bonding and separation method for manufacturing thin displays. IEEE Journal of the Electron Devices Society. 2020 Aug 19;8:917-24.
- [14] Boher P, Leroux T, Collomb Patton V, Bignon T, Blanc P. Viewing angle measurements on curved displays. Journal of Information Display. 2015 Oct 2;16(4):207-16.
- [15] Kujala S, Roto V, Väänänen-Vainio-Mattila K, Karapanos E, Sinnelä A. UX Curve: A method for evaluating long-term user experience. Interacting with computers. 2011 Sep 1;23(5):473-83.
- [16] Chen HW, Lee JH, Lin BY, Chen S, Wu ST. Liquid crystal display and organic light-emitting diode display: present status and future perspectives. Light: Science & Applications. 2018 Mar;7(3):17168-.
- [17] Yi J, Park S, Kyung G. Ambivalent effects of display curvature on smartphone usability. Applied Ergonomics. 2019 Jul 1;78:13-25.
- [18] Lee S. Ergonomic Design Guidelines for Non-flexible, Foldable, and Rollable Mobile Devices. 2019.
- [19] Lee S, Kyung G, Yi J, Choi D, Park S, Choi B, Lee S. Determining ergonomic smartphone forms with high grip comfort and attractive design. Human factors. 2019 Feb;61(1):90-104.
- [20] Chen JT, Yang SH. Method for debonding of thin glass substrate and carrier for manufacturing thin flexible displays. Journal of Materials Science: Materials in Electronics. 2018 Nov;29:18941-8.
- [21] Takeuchi K, Fujino M, Matsumoto Y, Suga T. Mechanism of bonding and debonding using surface activated bonding method with Si intermediate layer. Japanese Journal of Applied Physics. 2018 Mar 22;57(4S):04FC11.
- [22] Hsu TH, Yu KY, Lai YH, Wang WT, Lin YH. P-140: Lamination technology for flexible AMOLED. In SID Symposium Digest of Technical Papers 2017 May (Vol. 48, No. 1, pp. 1785-1788).
- [23] Kao SC, Li LJ, Hsieh MC, Zhang S, Tsai PM, Sun ZY, Wang DW. 71-1: Invited paper: the challenges of flexible OLED display development. In SID Symposium Digest of Technical Papers 2017 May (Vol. 48, No. 1, pp. 1034-1037).
- [24] Cho DH, Kwon OE, Park YS, Yu BG, Lee J, Moon J, Cho H, Lee H, Cho NS. Flexible integrated OLED substrates prepared by printing and plating process. Organic Electronics. 2017 Nov 1;50:170-6.
- [25] Ke TY, Kang T, Lee CT, Chen CY, Su WJ, Wang WT, Huang ZS, Wang JC, Hsu ST, Wang CL, Lai YH. 70-3: Distinguished Paper: Flexible OLED Display with 620 Degree Celsius LTPS TFT and Touch Sensor Manufactured by Weak Bonding Method. In SID Symposium Digest of Technical Papers 2020 Aug (Vol. 51, No. 1, pp. 1048-1051).
- [26] Cho HW, Lee I, Lee HJ, Kim MH, Park JH, Oh YR. 35-1: The Mechanism and Solution of Horizontal Line Defects by

- Mutual Interference of Flexible OLED and Touch Sensor. InSID Symposium Digest of Technical Papers 2020 Aug (Vol. 51, No. 1, pp. 489-492).
- [27] Wang S, Ma C, Yao Q, Wang L. 7.5: the application of metal mesh Manhattan patterns in flexible touch panel. InSID Symposium Digest of Technical Papers 2021 Feb (Vol. 52, pp. 53-56).
- [28] Kamada T, Hatsumi R, Watanabe K, Kawashima S, Katayama M, Adachi H, Ishitani T, Kusunoki K, Kubota D, Yamazaki S. 71-4: Distinguished Paper: OLED Display Incorporating Organic Image Sensor. InSID Symposium Digest of Technical Papers 2019 Jun (Vol. 50, No. 1, pp. 1011-1014).
- [29] Watanabe K, Iwaki Y, Uchida Y, Nakamura D, Ikeda H, Katayama M, Cho T, Miyake H, Hirakata Y, Yamazaki S. A foldable OLED display with an in-cell touch sensor having embedded metal-mesh electrodes. *Journal of the Society for Information Display*. 2016 Jan;24(1):12-20.
- [30] Jeong HJ, Han KL, Ok KC, Lee HM, Oh S, Park JS. Effect of mechanical stress on the stability of flexible InGaZnO thin-film transistors. *Journal of Information Display*. 2017 Apr 3;18(2):87-91.
- [31] Song J, Huang X, Han C, Yu Y, Su Y, Lai P. Recent Developments of Flexible InGaZnO Thin-Film Transistors. *physica status solidi (a)*. 2021 Apr;218(7):2000527.
- [32] Prevatte C, Radauscher E, Meitl MA, Gomez D, Ghosal K, Bonafede S, Raymond B, Moore T, Trindade AJ, Hines P, Bower CA. Miniature heterogeneous fan-out packages for high-performance, large-format systems. In 2017 IEEE 67th Electronic Components and Technology Conference (ECTC) 2017 May 30 (pp. 1098-1106). IEEE.
- [33] Ke TY, Lee CT, Cheng KN, Su WJ, Kang T, Wang WT, Liu CH, Lin YH. 82-2: Substrate-Free Flexible Electronics Manufacturing by Weak Bonding Method. InSID Symposium Digest of Technical Papers 2018 May (Vol. 49, No. 1, pp. 1106-1109).
- [34] Rodriguez Fernandez M, Zalama Casanova E, Gonzalez Alonso I. Review of display technologies focusing on power consumption. *Sustainability*. 2015 Aug 11;7(8):10854-75.
- [35] Huang DZ. Analysis of the Impact of Foldable Mobile Phones Design on People's Lives. In 2021 International Conference on Public Relations and Social Sciences (ICPRSS 2021) 2021 Oct 21 (pp. 1155-1160). Atlantis Press.
- [36] Wang S. Integrated content-aware image retargeting system. Laurentian University (Canada); 2012.
- [37] Kang LW, Weng MF, Jheng CL, Tseng CY, Ramesh SK, Gureja A, Hsu HC, Yeh CH. Content-aware image retargeting for image display on foldable mobile devices. *Procedia Computer Science*. 2015 Jan 1;56:104-10.
- [38] Bai PF, Hayes RA, Jin M, Shui L, Yi ZC, Wang L, Zhang X, Zhou G. Review of paper-like display technologies (invited review). *Progress in electromagnetics research*. 2014;147:95-116.
- [39] Zhao Z, Liu K, Liu Y, Guo Y, Liu Y. Intrinsically flexible displays: key materials and devices. *National Science Review*. 2022 Jun;9(6):nwac090.
- [40] Kim DY, Kim MJ, Sung G, Sun JY. Stretchable and reflective displays: materials, technologies and strategies. *Nano Convergence*. 2019 Dec;6(1):1-24.