Achieving Low Chroma Edges in Curved Cover Glass with Anti-Reflection and Anti-Scratch Properties

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Abstract
We have newly developed a multilayer thin-film coating design method for curved glass substrates used in smartphone displays. This innovative design achieves low chroma across all display regions, including both flat and curved parts, while incorporating anti-reflection (AR) functionality. It eliminates the characteristic deep red line typically observed in the curved regions of conventional AR multilayer coatings.

Author Keywords
Anti-reflection, Anti-scratch, Curved, Sputtering, Multilayer thin-film, Low chroma, Colorless

1. Introduction
AR coatings are a commonly used technology in products like eyeglasses and camera lenses but have seen limited adoption in smartphones. Applying AR coatings to the topmost surface of a display reduces external light reflections and enhances the transmittance of light emitted from the display, thereby improving display quality. However, in environments where wear is common, such as with mobile displays, AR coatings may instead lead to a decline in display quality over time. This is because the finely tuned properties collapse due to small scratches, making the scratched areas more noticeable due to the sharp change in reflectance or color. Therefore, in a mobile environment, AR coatings indispensably require anti-scratch (AS) properties [1].

A high nanoindentation hardness of AR coatings is generally required to satisfy AS properties. To address this, multilayer thin-film coatings produced by sputtering are considered the most industrially suitable approach due to their high quality and low manufacturing costs. Silicon nitride, silicon oxynitride, aluminum nitride and aluminum oxynitride are representative materials suitable for optical coatings while having high hardness in sputter [2,3]. In addition, there are studies on Al-Si-N and Al-Ge-N as nanocomposite materials for high hardness optical materials [4-7]. The multilayer thin-film structure is bound to have limitations, as meeting high hardness requirements while satisfying AR properties necessitates increasing the content of high-refraction and high-hardness materials as much as possible.

The recent curved design to improve the aesthetic appreciation of smartphone design adds one more technical challenge to it. The display with a curved edge consists of a flat part in the center and a curved part at the edge, in which case, AR coatings of the curved part do not maintain a constant thickness like the central flat part. The coating thickness of the curved part refers to the thickness of an angle perpendicular to the substrate. Figure 1(a) is an example of a curved cover glass. Figure 1(b) is a cross-sectional schematic illustration of AR coatings on glass at the curved edge, and the maximum slope of the curved part is about 45 degrees. Figure 1(c) is a normalized thickness according to the angle of the curved part when SiO_2 500 nm is deposited. The particles that are bombed during sputter deposition are perpendicular to the flat part. Therefore, the deposition thickness of the curved part decreases as the curved angle increases, and assuming that all particles are

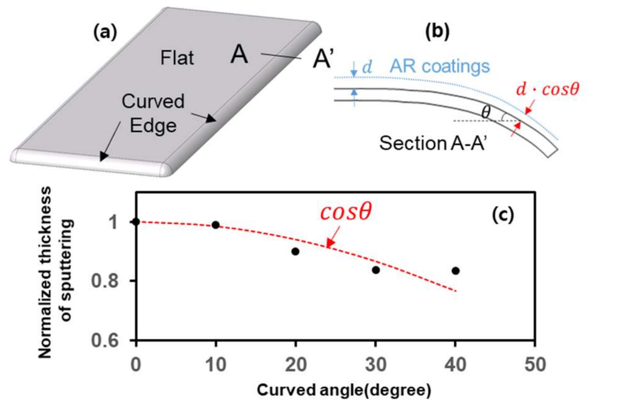

Figure 1. (a) Curved Cover Glass (b) Cross-sectional schematic illustration of AR coatings on glass at the curved edge (c) Sputtering thickness vs. curved angle

deposited only vertically, the thickness decreases by the cosine value of the curved angle. This makes the optical properties of the curved part different from the finely tuned optical properties of the flat part. The flat part is already adjusted so as not to have a specific reflective color, that is, to have low chroma. However, when the coating thickness decreases in the curved part, the chroma increases.

2. Results and discussion
A multilayer thin-film structure having low reflection and high hardness was designed and manufactured. For the design process, a custom-developed program was used, and the designed multilayer thin-film was deposited using Radical Assisted Sputtering (RAS) sputtering equipment (Optorun Co., Ltd.). Corning's Gorilla Glass (GG7) was used as the substrate. After depositing the Si thin-film with the same silicon target (3 targets, 10kW) in the RAS system, oxygen (350scm, 3kW) and nitrogen (350scm, 3kW) gas were injected respectively, to form SiO_2 and Si_3N_4 films repeatedly and alternately.

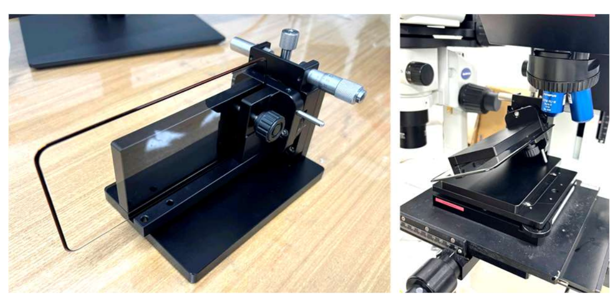

Figure 2. Micro-spectrophotometer of Olympus (USRM-RU-W) and a jig for tilting the sample at various angles to achieve perpendicular light incidence and reflection

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The reflective spectrum was measured using CM-3700A of Konica Minolta Ltd. for the flat part and USRM-RU-W micro-spectrophotometer of Olympus Ltd. for the curved part. In order to measure the spectrum of light reflected perpendicularly on the curved part, a custom jig was made as shown in Figure 2, allowing spectrum measurements at various curved angles. UNHT³ Standard of Anton Paar Ltd. was used to measure nanoindentation hardness.

Figure 3 shows a typical AS and AR multilayer thin-film coating consisting of an alternating structure between a low-refractive material, SiO_2 and a high-refractive material, Si_3N_4. By maximizing the total thickness of the high-hardness Si_3N_4 layer, we achieved a maximum hardness of 20GPa while simultaneously attaining a reflectance of 0.4%. However, in the curved part, a deep red line occurs as shown in the Figure 3(c), which is annoying to the eyes. This sample will be referred to as Sample A.

As seen n in Figure 4(a) showing the chroma (C* in CIELAB space) of the curved part of sample A, the value increases as the curved angle increases. An increase in C* means that the color becomes deeper. As shown in Figure 4(b), the reflective spectrum in the curved part is blue shifted due to the decrease in coating thickness as the curved angle increases. This is because the same interference effect occurs at a shorter wavelength with a larger refractive index as the thickness decreases. As a result of the blue shift of the reflective spectrum, the deep red line appears as the reflectance increases in the red region.

There are two ways to suppress this red color that hinders aesthetic appreciation of the appearance. One is to minimize the decrease in deposition thickness at the curved part. However, this cannot be considered an effective method from an industrial perspective. This is because commercially available sputtering systems are typically designed to achieve uniform deposition in a single direction. To achieve uniform deposition on both flat and curved parts, not only would additional modifications to the sputtering system incur increased costs, but the effective deposition area would also be reduced, leading to a decline in productivity. The second is to minimize spectral changes as shown in Figure 4(b) in a more technical way without additional modification of the sputtering system.

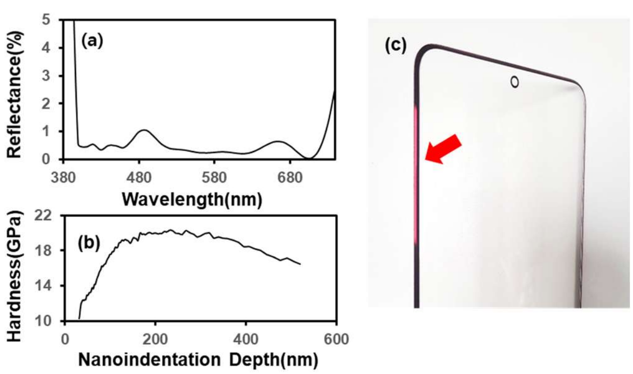

Figure 3. An AS and AR multilayer thin-film (Sample A) with (a) reflectance of 0.4% and (b) Max. 20GPa, and (c) a red line of the curved part

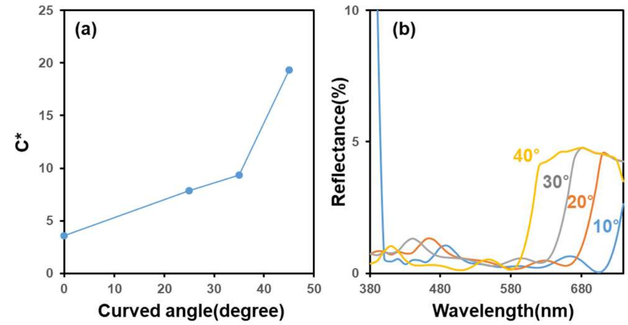

Figure 4. Changes in (a) Chroma and (b) Reflective spectrum according to the curved angle of Sample A

In general, AR coatings are designed to reduce reflectance in the visible light region and are not typically optimized to minimize reflectance in the near UV or near IR(NIR) regions. Therefore, when the reflective spectrum of a curved part shifts toward shorter wavelengths (blue shift) due to reduced deposition thickness, the NIR region, which exhibits relatively high reflectance, shifts into the visible red region, resulting in the appearance of red color. To suppress the occurrence of red color on the curved part, the reflectance of the flat part must be reduced even in the NIR region. However, this solution alone is insufficient, as color perception is an extremely sensitive property.

Even if the reflectance in the NIR region is reduced to minimize changes in reflectance in the red region caused by decreased deposition thickness, shifts in reflectance in the green and blue regions could still result in the appearance of colors other than red. In other words, it is necessary to carefully adjust the reflectance across the entire spectrum from blue to NIR regions. This concept can be more clearly expressed through the mathematical representation of the CIELAB color space, which defines color coordinates.

$$a^* = 500 \times \left(f\left(\frac{X}{X_n}\right) - f\left(\frac{Y}{Y_n}\right) \right)$$
$$b^* = 200 \times \left(f\left(\frac{Y}{Y_n}\right) - f\left(\frac{Z}{Z_n}\right) \right)$$
$$C^* = \sqrt{a^* + b^*} \qquad (1)$$
$$f(t) = \begin{cases} t^{1/3} & (t > 0.008856) \\ \frac{1}{3}\left(\frac{29}{6}\right)^2 + \frac{4}{29} & (t < 0.008856) \end{cases}$$

CIELAB (CIE L*a*b*) is the most complete and frequently used color space specified by the International Commission on Illumination in 1976. Eq. (1) represents the portion of the CIELAB space that defines the color coordinates. The values of a* and b* are functions of the color stimuli X, Y, and Z (red, green and blue, respectively). These quantitative values of color, denoted as a* and b*, are minimized (indicating achromaticity) when both values are zero, signifying the absence of chroma. To consider the scenario

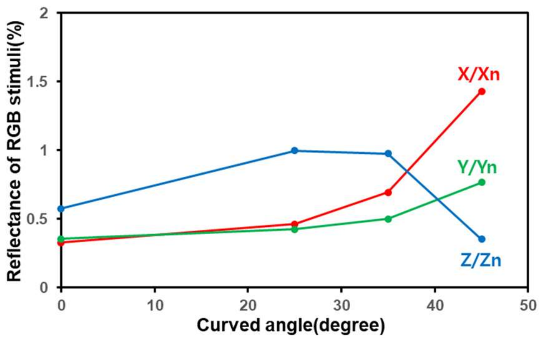

Figure 5. The reflectance of the RGB stimuli for the sample A as a function of the curved angle

relevant to our interest -measuring the reflective color coordinates - X, Y, and Z represent the reflected stimuli for RGB, while Xn, Yn, and Zn correspond to the stimuli of the incident light, such as the light source used for measuring the reflective spectrum. The condition for the curved part to appear colorless is to minimize the C* value, which requires that three reflected stimuli ratios (X/Xn, Y/Yn, Z/Zn) remain similar regardless of the curved angle. Figure 5 shows the reflectance of the RGB stimuli for the sample A as a function of the curved angle. As the curved angle increases, it indicates that the RGB stimuli fail to maintain the same value, which is the physical cause of the high C* value observed in Figure 4(a).

We designed a multilayer thin-film to ensure that the RGB stimuli reflectance values remain nearly equal, even with reduced coating thickness on the curved part. Ideally, the chroma of the curved part should be zero, but practically, it must be designed below a certain threshold to allow for design flexibility. However, there is no clear reference value for how low the chroma of the curved part should be to avoid visual trouble. The smartphone usage environment varies widely, with diverse ambient brightness levels around the display, as well as different angles and distances from which users view the curved part. At present, we lack sufficient empirical data on the perceptibility of color on the curved part. Nevertheless, without some reference, design becomes impossible. Therefore, even if there are incomplete or potential errors, a provisional reference value is necessary. This study proposes using the chroma of the curved part as a design reference when low reflection is achieved on the flat part through a single-layer MgF_2 coating (approximately 80nm) produced by e-beam evaporation [8]. The MgF_2 single-layer exhibits a relatively high reflectance of approximately 1.5% and very low hardness of around 3GPa.

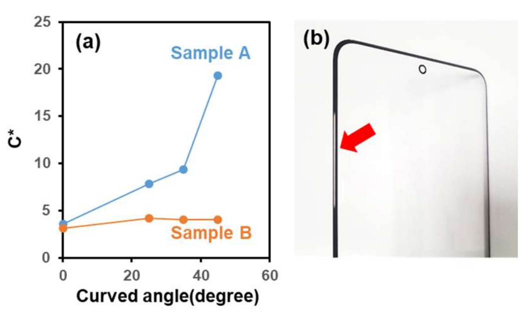

Figure 6. (a) The Chroma and (b) photo of the curved part of the MgF_2 single-layer coated by e-beam evaporation

However, its reflective spectrum is relatively flat from the visible to the NIR region, which prevents the appearance of red line on the curved part. In this case, the reference chroma value is set to 4.0 at a 45◦ on the curved part.

Using a custom-developed computing program for numerical analysis, various design outcomes were obtained, among which one design was fabricated through sputtering (referred as Sample C). The materials used were identical to those in Sample A, employing SiO_2 and Si_3N_4 in an alternating layered structure. Figure 7(a) shows the reflective spectrum at different curved angles. Despite the blue shift, the reflectance in the red region does not vary significantly, resulting in minimal coloration, as shown in Figure 7(b). This is attributed to the similar values of reflectance of RGB stimuli across the angles of the curved part, as depicted in Figure 7(c). Figure 7(d) compares the chroma characteristics of Samples A, B, and C on the curved part. The reflectance of Sample C is 0.9%, and its maximum nanoindentation hardness reaches 12GPa.

The total thickness of Si_3N_4 in sample A is approximately 850 nm, whereas that of sample C is only about 120 nm. As a result, the nanoindentation hardness of sample A reaches 20 GPa, while that of sample C is lower at 12 GPa. This is merely an initial design stage and we have outlined a blueprint to increase the hardness to 18 GPa to ensure sufficient AS performance. However, we have yet to identify a design capable of exceeding 20 GPa. This resembles a "balloon effect," where introducing a new boundary condition (chroma characteristics of the curved part) shifts the existing boundary conditions (AR and AS properties of the flat part) to establish a new balance. This reflects a structural limitation imposed by the system, including the materials, fabrication methods and alternating layered structure proposed in this study.

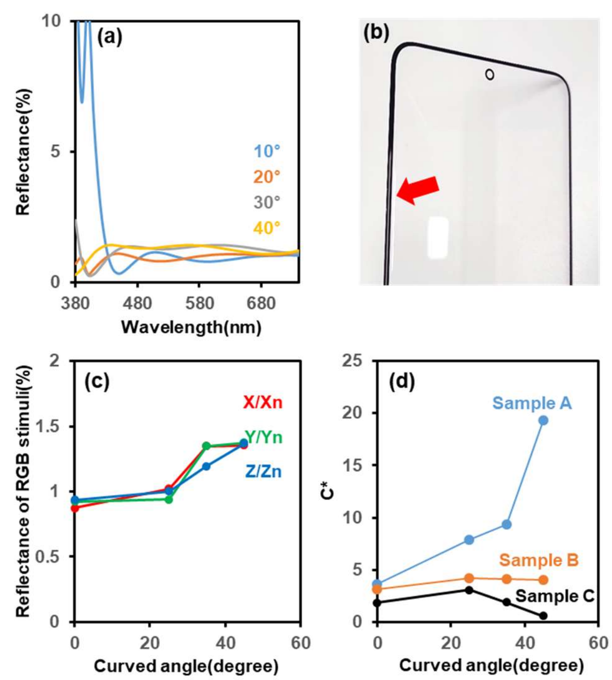

Figure 7. A multilayer thin-film (Sample C) in which the chroma of the curved part was suppressed was fabricated using sputtering. (a) The reflective Spectra, (b) The photo of the curved part, (c) The reflectance of the RGB stimuli, (d) The comparison of C* of sample A, B and C

As mentioned earlier, we lack sufficient empirical data on the perceptibility of color on the curved part. There is still a possibility of excessively suppressing chroma, leading to an unnecessary increase of reflectance and decrease of hardness or vice versa. This study does not aim to propose an optimal point between the two, but instead demonstrates acceptable AR and AS properties on the flat part along with chroma characteristics on the curved part. In doing so, we have identified a technical solution to address the challenges arising from integrating curved designs in smartphones with AR and AS properties in the cover glass. To overcome the system's limitations and achieve even better properties, such as improved reflectance, we are conducting follow-up research on new materials and structures.

3. Conclusion

To enhance display quality, cover glass with AR and AS properties is being incorporated into some high-end smartphones. As a design differentiation feature, high-end smartphones adopt curved-edge designs. However, conventional AR coatings with multilayer thin-films tend to produce a red line on the curved part. This issue has been resolved by employing a design method that maintains a similar reflectance variation of the RGB stimuli values of external light, regardless of the curved angle. It is noteworthy that this was achieved without altering the fabrication process or materials, using conventional reactive sputtering methods and conventional optical sputtering materials. The final properties of the multilayer thin-film achieved reflectance of 0.9%, hardness of 12 GPa, and chroma below 3 at a 45° angle on the curved part.

This report is not the final or fully optimized output of our development but rather serves as a mid-term progress report. AR and AS properties are in a trade-off relationship with the chroma of curved part, and we are currently working on optimizing this balance. Furthermore, we are examining how variations in optical materials and structures influence both optical and mechanical properties.

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