Antireflection displays with ambient contrast enhancement for extended device battery lifetime and reduced energy consumption

Karl W. Koch | Brooke Hathaway | Carlo Kosik Williams | Jaymin Amin | Alexandre Mayolet | Deeder Aurongzeb | Joseph McDonald | Shandon Hart

1Science & Technology, Corning Incorporated, Corning, New York, USA
2Mobile & Consumer Devices, Dell Technologies, Austin, Texas, USA
3Department of Electrical Engineering, University of Colorado Boulder, Boulder, Colorado, USA

Correspondence
Shandon Hart, Science & Technology, Corning Incorporated, Corning, NY 14831, USA.
Email: hartsd@corning.com

Abstract
Antireflection (AR) coatings can improve the viewing experience of a display, including mobile electronic devices such as smartphones, tablets, and notebook computers. The requirements for visual quality, color control, and scratch resistance are more stringent for these mobile devices than they are for nondisplay applications such as solar panels, due in part to the high sensitivity of the human eye to minor defects or color variations in display applications. At the same time, these mobile devices comprise a growing share of global energy consumption. The display can consume over 30% of the total power of a notebook computer and can exceed 50% of the power consumption of a smartphone, though this is highly dependent on usage conditions. Significant work has been invested in optimizing mobile device energy consumption and battery lifetime using active control of display output, under consideration of the impacts on perceived image quality.

KEYWORDS
antireflection, battery, display visibility, energy, outdoor, reflection

1 INTRODUCTION

Antireflection (AR) coatings have a long and rich history and have continued to advance in recent years for applications as diverse as microscope lenses, eyeglasses, photovoltaics, and electronic displays. However, the majority of smartphones in service today still do not incorporate AR coatings, due to cost and durability concerns. Recently, advances in optical coating design, precise control of uniformity and color, high coating durability on glass substrates, and large-area vacuum coating technologies are increasing the use of AR coatings in visually and mechanically demanding applications, such as in the widespread touch screen displays protected with chemically strengthened glass used in smartphones, tablets, and notebook computers.

Received: 23 October 2019 Revised: 25 February 2020 Accepted: 8 March 2020
DOI: 10.1002/jsid.892

© 2020 The Authors. Journal of the Society for Information Display published by Wiley Periodicals LLC on behalf of Society for Information Display
These methods may in some cases make use of image and color appearance models to calculate the appropriate scaling of display output, accounting for energy consumption impacts. Here, we provide an initial quantification of the energy savings and battery lifetime improvement that can be obtained by reducing the front-surface photopic reflectance of mobile devices below 0.5% using state-of-the-art AR coating on glass technology, with an experimental focus on tablet computers using liquid crystal displays. Our results are correlated to the human user experience of display contrast using a perceptual contrast length (PCL) model. We believe that these results should translate to a broad variety of displays and devices beyond the tablet computers tested here, including organic light-emitting diodes (OLEDs), smartphones, and smartwatches. These results have significant implications for improved user experience with mobile devices and provide new insight into the true economic value as well as the global energy savings potential of AR coatings for mobile phone and computing devices.

2 EXPERIMENTAL METHODS

Optical performance and battery lifetime comparisons were carried out on two Dell Latitude tablet computers, both having typical touch screen cover glass bonded onto liquid crystal display (LCD) backplanes: one consisting of Corning® Gorilla® Glass 3 (denoted as “GG” display below) having a front-surface reflectance of ~4% that is typical of glass, and the other consisting of Corning® Gorilla® Glass DX (denoted as “DX” display below), a specialized version of chemically strengthened glass with a durable AR coating having ~0.40% front-surface photopic average reflectance. It should be noted that for display contrast measurements under ambient lighting, it is not only the first-surface reflectance that matters but also reflectance from buried layers such as touch sensor and display architecture. Modern touch screen devices typically have at least ~0.5% reflectance from these buried layers, which would add to the front-surface reflectance values quoted above.

To perform ambient contrast measurements, a variable illuminance level, wide area, diffuse light source was used to create a controlled amount of ambient illumination incident on the display. The display was driven in white and dark modes for contrast measurement, with the brightness of the display adjusted to simulate different power saving modes. To allow for the wide area geometry of the illumination apparatus, the display luminance levels were measured at a 20° angle from the normal axis of the display. Mobile displays typically have the highest brightness along the normal (0°) viewing axis. For reference, a 20° luminance value of ~260 cd/m² is shown here corresponds to a 0° luminance value of ~370 cd/m², and the other luminance values scale similarly. Display luminance values quoted throughout the remainder of this paper correspond to the luminance measured at 20°. The light emitted from the display together with the reflected light was measured using a Photo Research: SpectraScan PR-745. The direct reflected image of the diffuse ambient light source was visible and collected by the radiometer, making this lighting condition analogous to a user experience scenario where the user’s eye directly sees the reflection of a bright white interior wall or a cloudy outdoor sky being reflected from their device. The contrast and perceived image quality metrics reported here have also been verified with similar measurements performed on more than 20 display devices from more than 10 different manufacturers, with similar trends observed across all platforms. Thus, the results shown here are illustrative of repeatable trends for a wide variety of mobile devices.

3 RESULTS AND DISCUSSION

Figure 1 shows the statistical fabrication repeatability of individual AR-coated glass samples of the type used in this study. Over 90 measurements were taken from 10 different parts, each part representing one of 10 unique coating fabrication runs. Figure 1 shows transmittance and first-surface reflectance, with the first-surface reflectance falling in a controlled range of ~0.36% to ~0.44%. This level of control should correlate to a <10% variation in the luminance and contrast of test displays under ambient lighting.

The display ambient contrast ratio (ACR) is conventionally defined as the ratio of display luminance in the fully on “white” state ($L_w$) to the display luminance in the fully black state ($L_k$), that is, $ACR = L_w/L_k$. Under ambient lighting, the ACR for the low-reflectance display is higher primarily because the display reflects less of the ambient light, making $L_k$ smaller (the blacks of the display appear to be more black), which increases contrast ratio (CR). Second, the low-reflectance display can transmit more light, making $L_w$ slightly higher. $L_k$ tends to have the larger impact on CR in this scenario. In addition to CR improvements, the color gamut of the display under ambient lighting is improved by reduced reflectance. This is because the ambient lighting “washes out” the color saturation of the images, so lowering the reflectance of ambient light reduces this washout effect, yielding a larger color gamut compared with an uncoated display. Figure 2 visually illustrates these effects using measured images, showing the improved contrast and viewability of an AR-coated display compared with a...
standard display under the same ambient lighting and display output conditions. Using this understanding, we use ACR as a first step to conceptually illustrate how display image quality can be related to energy, power, and battery lifetime savings.

Since ACR is a simple ratio of $L_w/L_k$, we see for a reduced $L_k$, such as can be achieved with a low-reflectance display, the luminance output of the display ($L_D$) can be reduced by a similar factor, and the realized ACR will be the same. Thus, if $L_k$ under ambient lighting can be reduced by a factor of 2 due to lower reflectance, then $L_D$ can also be reduced by a similar factor of 2, for example, from 400 to 200 cd/m², while achieving the ACR of an uncoated display at 400 cd/m². Figures 3 and 4 illustrate this effect for the exemplary displays tested in this study, the AR-coated “DX” display and the conventional “GG” display having no AR coating. Over a wide range of ambient lighting levels from 200 to 1,000 lux, the “DX” display can be operated at less than half of the luminance output of the “GG” display while preserving the same or better ACR.

Conventional ACR is only one measure of display performance. Ideally, a complete display user experience model would combine all of the elements that go into a user’s perception of display performance and quality, such as a model that combines perceived contrast ratio, perceived brightness, and perceived color gamut, including the changes to the user’s eyes and perception that can be caused by ambient environment and displayed content. Various color and image appearance models have been developed to support these analyses, such as

---

**FIGURE 1** Measured transmission and first-surface reflection for >30 fabricated antireflection (AR) coating on glass samples, illustrating the controlled properties of coatings of the type used in this study.

**FIGURE 2** Measured images illustrating ambient contrast ratio of “DX” antireflection (AR) display versus standard “GG” display under 400-lux ambient illumination, corresponding to bright indoor lighting, with both displays set to an output luminance level of ~250 cd/m². Images and luminance values were measured at ~20° viewing angle to accommodate the geometry of the large diffuse white light source used to provide uniform ambient illumination.

**FIGURE 3** Measured ambient contrast ratio of “DX” antireflection (AR) display versus standard “GG” display under 400-lux ambient illumination (corresponding to bright indoor lighting). Under these conditions, the brightness of a “GG” display operating at ~250 cd/m² can be lowered to about 105 cd/m² (~58% reduction) for the “DX” display while maintaining an equivalent ambient contrast ratio, as indicated by the arrows. The dashed lines represent the trends expected from theoretical calculation according to ambient contrast ratio (ACR) = $L_w/L_k$. 

**FIGURE 4** Linear logarithmic ambient contrast ratio, 400-lux illuminance graph comparing the ambient contrast ratio of the “DX” and “GG” displays under 400-lux ambient illumination.
CIECAM02\textsuperscript{14} and iCAM\textsuperscript{06,15} and new models may yet be developed. One model that has been proposed as an improved measure of human perception of contrast is PCL. PCL has been shown to have a higher correlation to human perception of display contrast than the straightforward ratio of luminance such as ACR, especially under various levels of ambient illumination.\textsuperscript{16,17} Here, we use the PCL calculation method of Shin et al.,\textsuperscript{16} modeled after the work of Bartleson and Breneman,\textsuperscript{18} relating human perception of brightness and contrast to measured luminance. Perceived brightness ($B_Q$) was calculated from measured luminance according to the following equation:

$$B_Q = \frac{10^{2.037L_Q^{0.1401}}}{\text{antilog}_{10}^{\text{gexp}\left( f \log_{10}L_Q \right)}}$$

where $g = 0.99+0.124(L_W)^{0.312}$, $f = -0.1121 - 0.0827(L_W)^{0.093}$, $L_W$ is the white luminance of a test case in cd/m$^2$, and $L_Q$ is the luminance of test element $Q$ (e.g., a black or white element) in candela per square meter.

PCL is then calculated by direct subtraction of $B_Q$ for the black screen element from $B_Q$ for the white screen element. Figures 5 and 6 give the PCL values for our anti-reflected “DX” versus standard “GG” displays at different display luminance output levels and under varying intensity of ambient lighting.

The conversion of display output to battery lifetime savings (and therefore energy savings) is highly dependent on device architecture as well as the type of content and use mode of the device.\textsuperscript{9,10} For the tablet computer...
devices tested here, under the operating mode of streaming video content, we observed an ~8% battery lifetime extension for every 50 cd/m² reduction in display luminance (~25% luminance reduction), as shown in Figure 7. Estimating from these data, an ~30% improvement in PCL as shown in Figure 6 can be used to lower display output luminance by about 138 cd/m² under 1,000-lux (typical cloudy daylight or bright indoor) ambient illumination, while maintaining a similar user experience of display contrast according to the PCL model. This reduction of 138 cd/m² corresponds to a battery lifetime savings of ~22% or more in streaming video mode for the test device used, following the data summarized in Figure 7.

Figure 8 brings together various pieces of understanding illustrated above and compares the PCL of a low-power “DX” AR display versus a higher power “GG” standard display under varying ambient illumination levels. Figure 8 compares a “DX” AR display having a luminance set to 136 cd/m² to a standard “GG” display having a luminance of 240 cd/m². The PCL for the two displays is nearly identical over a broad range of ambient illuminance from 400 to 1,000 lux, even though the “DX” AR display has ~43% lower luminance setting. The advantage of the “DX” AR display is consistent over the 400–1,000 lux of ambient illumination range and slightly larger at higher ambient illuminance levels. In addition to the small PCL variation as shown in Figure 8, (<1 between the two displays in this range), the difference in perceived brightness of the white screen between the standard display and the antireflected display, $B_Q(“GG,” white) − B_Q(“DX,” white) is less than ~3, which is within the range of perceived brightness variation seen for displays judged to be visually similar in human perception studies.16 This ~43% display luminance reduction, from 240 to 136 cd/m², corresponds to a potential battery lifetime increase of ~16.5% for our test devices in streaming video mode, following the battery lifetime data summarized in Figure 7.

4 | CONCLUSION

Recently developed durable AR coatings can improve the viewing experience of displays, including those on mobile electronic devices that are typically operated on battery power, without sacrificing the scratch resistance and other durability features expected from modern touch screen devices protected by chemically strengthened glass. In this work, we showed that with a ~50% higher ACR and a ~30% higher PCL, an AR-based display can be operated at >30% lower brightness than a non-AR display based on the PCL model of human perception, resulting in a potential improvement of >15% in device battery life, with a similar proportion of energy savings. The energy savings potential of AR-coated displays increases with higher ambient Illumination level and also scales with the proportion of device energy that is consumed by the display. This work has significant implications for the true economic value of durable AR coatings in display applications, where usage of AR coatings is still limited today by cost and durability concerns. Future improvements may include reduced reflectance from AR coating innovation, as well as reduced reflectance from buried
subsurface display layers and touch sensor architecture. These conclusions may be further refined in the future by direct human perception studies of AR-coated displays under various lighting conditions or from new enhancements of human perception models.

ACKNOWLEDGMENTS
The authors would like to acknowledge Lin Lin, Nicholas Walker, Charles Paulson, James Price, Ken Chauvin, Tom Whelan, Heather Decker, Kevin Reiman, Robert Bellman, Loretta Moses, Bill McKendrick, Arnette Brooks, Tomo Ishikawa, Robert Schweiger, Ray Greene, Albert Fahey, Binwei Zhang, Ananth Subramanian, Josh Jacobs, Jum Kim, Sanjay Sinha, Jim West, Florence Verrier, David Weidman, Robert Lee, and Odessa Petzold for their invaluable contributions to experiments, analysis, logistical support, and informative discussions.

DISCLOSURES
The authors are current or recent employees of Corning Incorporated and Dell Technologies, commercial organizations which may choose to market or sell technical products related to the subject matter of this article.

ORCID
Shandon Hart @ https://orcid.org/0000-0003-2963-4691

REFERENCES
1. Raut HK, Ganesh VA, Nair AS, Ramakrishna S. Anti-reflective coatings: A critical, in-depth review. Energ Environ Sci. 2011;4:3779–3804.
2. Macleod HA. Thin-film optical filters Boca Raton, FL: CRC press; 2010.
3. Baumeister PW. Methods of altering the characteristics of a multilayer stack. J Opt Soc Am A. 1962;52:1149–1152.
4. Southwell WH. Coating design using very thin high-and low-index layers. Appl Optics. 1985;24:457–460.
5. Bellman RA, Hart SD, Koch KW III, Paulson CA. U.S. Patent. 2015;9,079,802.
6. Hart SD, Koch KW III, Paulson CA, Price JJ, US Patent. 2016 9:335–444.
7. Paulson CA, Price JJ, Koch KW, et al. Industrial-grade anti-reflection coatings with extreme scratch resistance. Opt Lett. 2019;44:5977–5980.
8. Fehske A, Fettweis G, Malmodin J, Biczok G. The global footprint of mobile communications: The ecological and economic perspective. IEEE Commun Mag. 2011;49(8):55–62.
9. Bhowmik AK, Brennan RJ. System-level display power reduction technologies for portable computing and communications devices, In 2007 IEEE international conference on portable information devices, IEEE, 1-5 2007.
10. Carroll A, Heiser G. An analysis of power consumption in a smartphone. In USENIX annual technical conference 2010 14:21.
11. Chondro P, Chang CH, Ruan SI, Shen CA. Advanced multimedia power saving method using dynamic pixel dimmer on AMOLED Displays. IEEE Trans Circuits Syst Video Technol. 2017;28(9):2200–2209.
12. Kang S-J. Image-quality-based power control technique for organic light emitting diode displays. J Display Technol. 2015;11(1):104–109.
13. Park M, Song M. Saving power in video playback on OLED displays by acceptable changes to perceived brightness. J Display Technol. 2015;12(5):483–490.
14. Wu R-C, Wardman RH. Proposed modification to the CIECAM02 colour appearance model to include the simultaneous contrast effects. In Color Research & Application: Endorsed by Inter-Society Color Council, The Colour Group (Great Britain), Canadian Society for Color, Color Science Association of Japan, Dutch Society for the Study of Color, The Swedish Colour Centre Foundation, Colour Society of Australia, Centre Français de la Couleur32.2, 2007 121–129.
15. Kuang J, Johnson GM, Fairchild MD. iCAM06: A refined image appearance model for HDR image rendering. J Vis Commun Image Rep. 2007;18(5):406–414.
16. Shin M, Chong JH, Yang SA, Lee E, Lee SB, Berkeley BH. P-48: A new approach toward visual clarity assessment using perceptual contrast length. In: SID Symposium Digest of Technical Papers 42(1) Oxford, UK: Blackwell Publishing Ltd.; 2011. pp. 1277–1280.
17. Shin M, Yang SA, Kim SY, Chong JH, Lee SB, Kim SS. P-72: Method for perceptual contrast measurement under different ambient conditions. In: SID Symposium Digest of Technical Papers 41(1) Oxford, UK: Blackwell Publishing Ltd.; 2010. pp. 1516–1519.
18. Bartleson CJ, Breneman EJ. Brightness perception in complex fields. J Opt Soc Am A. 1967;57(7):953–957.

AUTHOR BIOGRAPHIES

Karl W. Koch received a PhD studying at the Institute of Optics at the University of Rochester. He is currently a senior research associate within the Applied Optical Physics Directorate of the Science and Technology division of Corning Incorporated, working in the area of optical physics and waveguides.

Brooke Hathaway was a senior research technician for the Applied Optical Physics group at Corning Incorporated. She graduated from the University of California, San Diego, in 2017 with a BS in Nano Engineering and is now pursuing a MS degree in Optics from the Department of Electrical Engineering at the University of Colorado, Boulder, as well as a career in optical engineering.
Carlo Kosik Williams is a thin-film and surfaces research project manager within the Science and Technology division at Corning Incorporated. Prior to Corning, he obtained his PhD, MS, and BS degrees from the Department of Electrical and Computer Engineering at the University of Rochester in New York.

Jaymin Amin received a PhD in optoelectronics from the University of Southampton, UK. He is currently a vice president of technology and product development for Corning Specialty Materials.

Alexandre Mayolet received a PhD in inorganic materials from the University of Paris XI, France. He is currently the program manager for Corning Specialty Materials.

Deeder Aurongzeb is a Distinguished Engineer at Dell Technologies focusing on long-term hardware innovation and strategy. He has over 30 peer reviewed publications and over 20 conference proceedings from device physics to sustainability. He holds over 150 granted patents in various hardware and device interaction technologies and was recognized as 2016 Dell Inventor of the Year.

Joe McDonald is the User Interface Senior Principal Engineer for high-end consumer PCs at Dell Technologies in Austin, TX. In this role, Joe works to improve user experiences by informing the design of more useful, valuable, and feasible technologies. Joe holds a PhD in Human Factors from the Georgia Institute of Technology, with an emphasis on applied cognition and user behavior.

Shandon Hart is currently a Research Associate for Corning Incorporated. He received his BS in Ceramic Engineering from Alfred University and his PhD in Materials Science from the Massachusetts Institute of Technology. He is a coinventor on 47 granted US patents and 94 published or pending US patent applications.

How to cite this article: Koch KW, Hathaway B, Kosik Williams C, et al. Antireflection displays with ambient contrast enhancement for extended device battery lifetime and reduced energy consumption. J Soc Inf Display. 2020;28:801–807. https://doi.org/10.1002/jsid.892