# 3M Advanced Conductor Technology

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## Abstract

The miniaturization of portable electronic devices, including convergence of functions, integration of packaging and pace of innovation demand reduction of weight and thickness of individual components, as well as performance advantages not previously seen. Of particular interest are film-based transparent conductors with high transparency, neutral color, low electrical resistance and minimal visible contrast between patterned and unpatterned regions. In this presentation we will discuss one approach to meeting these requirements for electronic device applications with 3M's Advanced Conductor Technology.

## Introduction

As the application of touch screen displays has expanded beyond portable smartphones and tablets to uses in common household appliances, the medical field and heavy industry, so have the requirements for higher performance devices and products. These include improved viewing capabilities for higher image resolution as well as improved durability as touch screens are applied in longer warrantee products such as kitchen appliances. For portable applications, the weight and thickness of the products are of high importance pushing the boundaries for the materials used to make the displays. The ability to make the displays flexible further opens the technology to other markets. To address the weight and flexibility needs, the transparent conductive layers comprising the touch sensors are formed on polymer substrates, in particular polyethylene terephthalate (PET), rather than glass.

As the applications move to increased display sizes, maintaining high response speed performance while maintaining or improving image quality is difficult partially due to constraints of the transparent conductors. In particular, the needs include:

1) Improved ITO or transparent conductor (TC) conductivity. For large screen applications, this is required for high speed processing of signals and touch sensitivity,
2) Maximizing transparency of the TC layers, and
3) Minimizing contrast between conductive and non-conductive areas after patterning to lower conductor pattern visibility, increase viewing performance and reducing power consumption.

While there has been significant work on thin metal nanowire grids (1,2), conductive polymers (3), carbon nanotubes (4,5), and graphene (6) to develop TCO's with lower sheet resistances for higher speed performance, projections still suggest a significant demand for ITO based films in the coming years (7). As an ITO based alternative to single layer ITO, 3M has developed a flexible Advanced Conductor technology for improvement of its Large Area Multi-Touch Display Screens as well as a product for other smaller display applications. In this manuscript, this technology and its benefits will be reviewed.

**Laboratory Equipment**

The experimental work to develop this thin film technology was completed at 3M's Corporate Research Process Laboratory (CRPL). CRPL has multiple web coaters with capabilities of completing thin film depositions using a variety of different PVD, PECVD and other thin film deposition techniques. In particular, each of the machines are capable of making indium tin oxides (ITO) and other transparent conducting layer structures on narrow webs of different materials. The layers were typically prepared using DC or AC sputtering techniques. In-line spectrometers and conductivity monitoring devices allow for real time measurement of optical and electrical properties of the multi-layer stacks and on-the-fly adjustment of deposition parameters to achieve the desired optical performance. Using these machines, CRPL has formed many strategic alignment programs within and outside 3M. In particular, CRPL has worked with key partner divisions in 3M to not only commercialize the developments and apply them in 3M products but also assist the divisions in continuous manufacturing improvement projects.

**Advanced Conductor**

The basic 3M Advance Conductor is comprised of a three sputtered layers on a polyethylene terephthalate (PET) substrate as is shown in Figure 1. The ITO and SiOx layers are prepared using pulsed DC or AC sputtering with moderate power levels to maintain moderate deposition rates while controlling the level of oxygen ion bombardment known to lead to poorer ITO performance (8). Optimization of the high n/low n/high n construction can lead to similar optical properties to those for the PET substrate and high transparency for the entire stack. This is shown in Figure 2 where modeled transmittance data as a function of wavelength for uncoated PET is compared to PET coated with the Advanced Conductor and standard ITO. The modeling was done using Essential MacLeod software. Comparing films with similar sheet resistances, one can see that there is a significant drop in transmittance when PET is coated with standard ITO. However, use of the Advanced Conductor structure does not lead a decrease and can lead to transmittance greater than obtained with the uncoated PET over wavelengths of 450-700nm. It needs to be recognized that in order to achieve desired sheet resistances, transmittance values will be lower than that for the PET.


Figure 1. Advanced Conductor Construction.

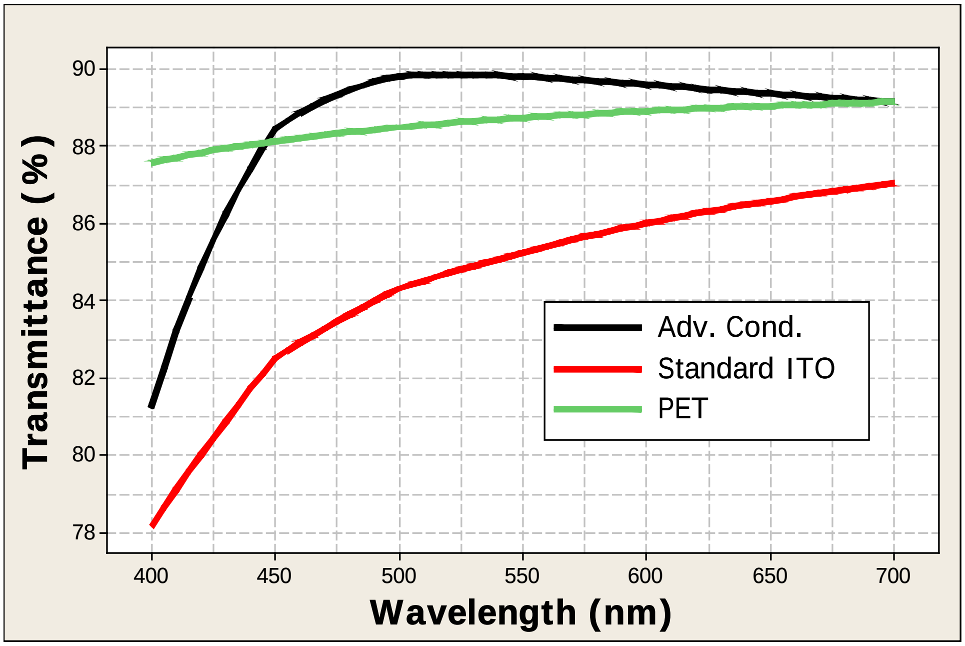


Figure 2. Modeled transmittance vs. wavelength of PET uncoated, coated with standard ITO and coated with Advanced Conductor.

Figure 3 shows the relationship between transmission and sheet resistance for both the Advanced Conductor and ITO films made at 3M. For all of the data shown in the figure, films were deposited on PET substrates and the transmission values are average values calculated using the ISO 13468 compensation method (9). For ITO, the trade-off between low sheet resistances and lower light transmission has been well documented. (10) It is also well known that the peak performance of ITO on low temperature substrates is achieved through annealing procedures such as hour long heat (11), flash lamp (12) or laser pulse (13). For the data in Figure 3, the ITO films were annealed in atmosphere at 150 °C for 90 to 120 minutes. For the optimal processing conditions, Advanced Conductor with sheet resistances of 130 Ω/□ and transparency values of 92% have been achieved, significantly better than the annealed ITO films. The ability to achieve lower sheet resistances while maintaining transmission values greater than 90% with the Advanced Conductor demonstrates its superiority for high speed device performance. In terms of processing advantages, the low sheet resistance are achieved without an annealing procedure. This is particularly important for polymer based substrates which can limit annealing processes to long processing steps and/or processes requiring significant capital costs.

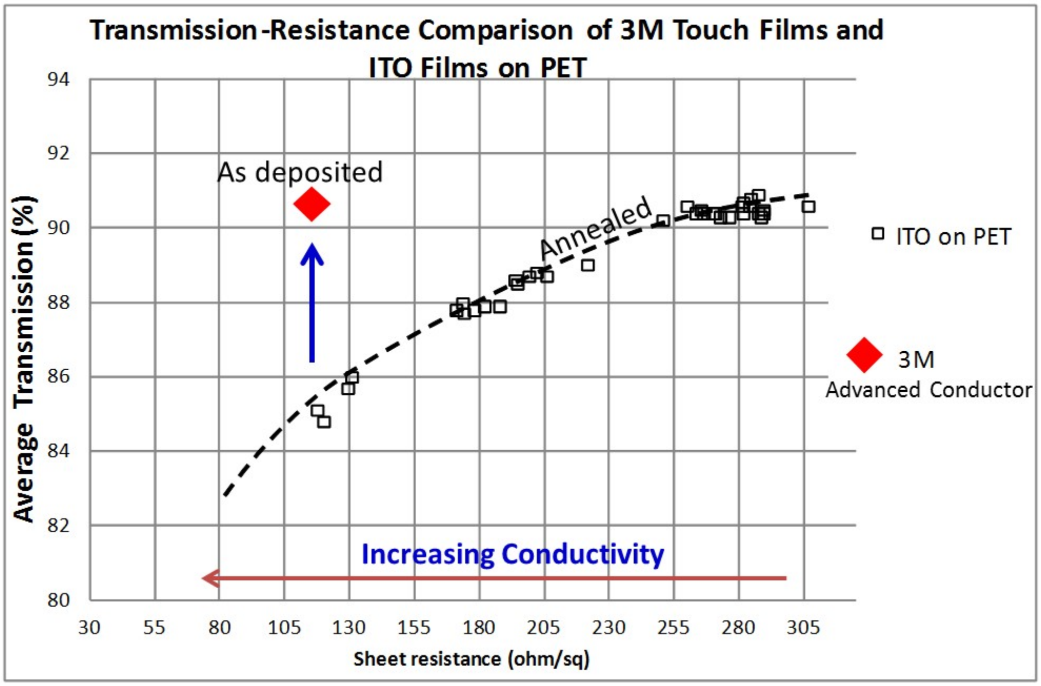


Figure 3. Transmission values as a function of sheet resistance for ITO and Advanced Conductor.

Other benefits in using the Advanced Conductor over standard annealed ITO were observed in the reflected and transmitted light color. For display applications in which patterning is required, having the light transmitted through and reflected from the transparent conductor coated PET closely match that from the etched regions without transparent conductor is a key for minimizing pattern recognition. In particular, minimizing differences in the transmitted b* color component is particularly important to make the reflected and transmitted light more color neutral. Figure 4 shows the reflected b* light from PET films coated with Advanced Conductor and ITO (annealed) as a function of sheet resistance. The amount of measured transmitted light through the transparent conductor coated PET films is shown in Figure 5. As conditions are altered to minimize sheet resistances of the ITO, the amount of reflected and transmitted b* light increases. Since the amount of reflected and transmitted b* light is close to 0 for the PET film, the undesired pattern recognition increases with the decreasing sheet resistance. With the ability to tune the optical characteristics through alteration of the thicknesses of the ITO and SiOx layers, both the reflected and transmitted b* values are lower for the Advanced Conductor coated films reducing the pattern recognition leading to improved display appearance.

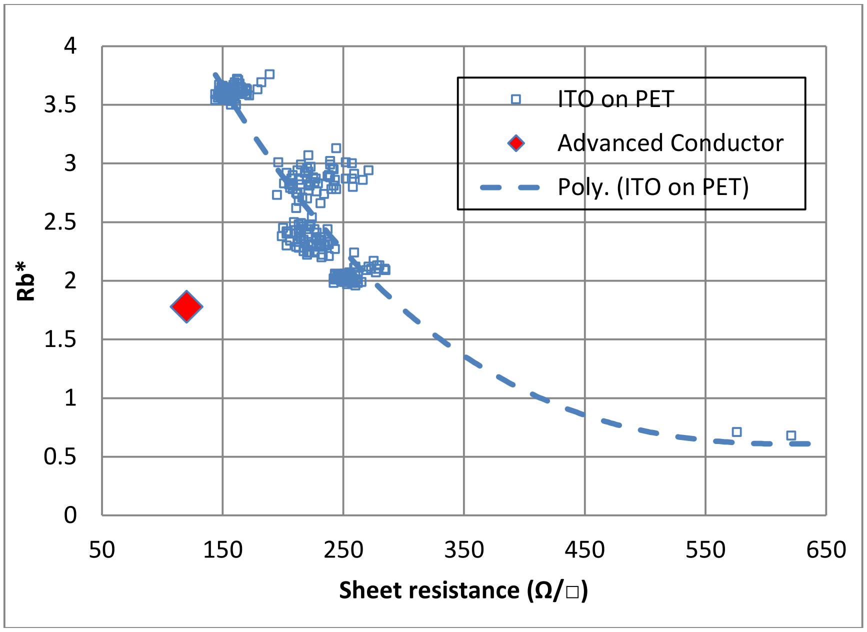


Figure 4. Reflected b* light as a function of sheet resistance for Advance Conductor and ITO coated PET.

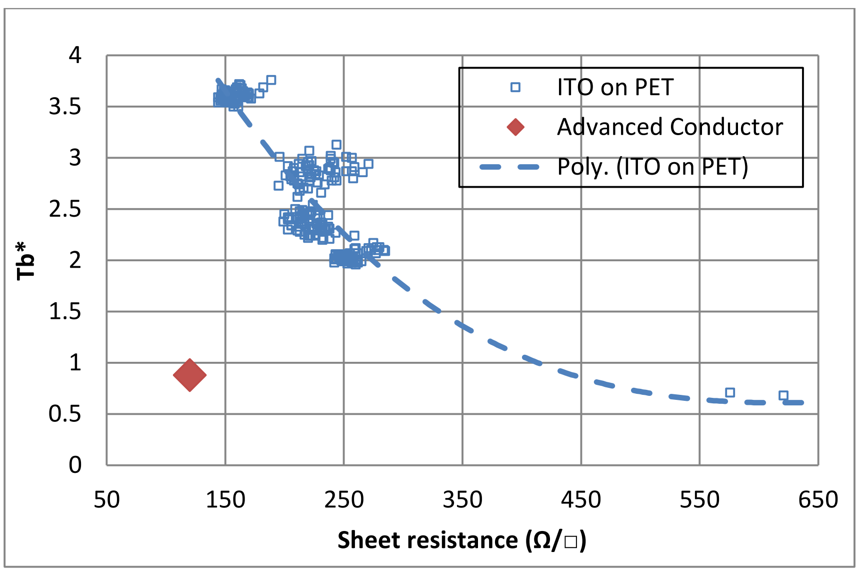


Figure 5. Reflected b* light as a function of sheet resistance for Advance Conductor and ITO coated PET.

While the pattern recognition is reduced with the ITO/SiOx/ITO construction, the reflected and transmitted b* values are still significantly different from the PET substrate. In order to further reduce the transmitted and reflected light differences between the patterned and unpatterned areas, a high n/low n stack can be added between the PET and the Advanced Conductor. Figure 6 compares the difference in reflectance from the patterned area (without Advanced Conductor) and the unpatterned areas (with Advanced Conductor) for the fabricated structures with and without the high n/low n stack. Also included in the figure are values for an ITO coated PET film with the ITO thickness matching the total thickness of the ITO layers in the Advanced Conductor. The reduced difference in reflection and thus pattern recognition with Advanced Conductor over ITO can be noted as well as the additional loss with the high n/low n optical stack. With the high n/low n stack, the reflection for the Advanced Conductor nearly matches that from the PET substrate leading to virtually no recognition of the patterned layers.

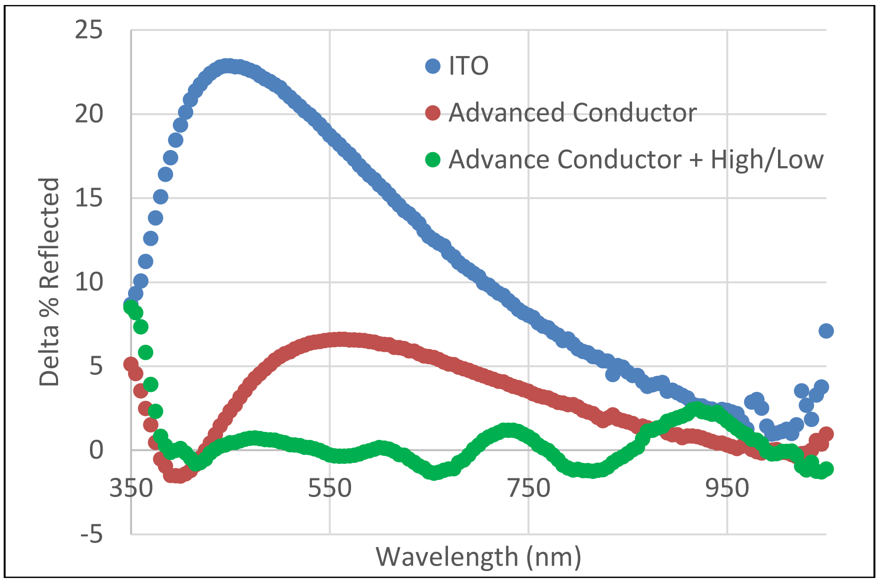


Figure 6. Differences in reflection from patterned and unpattern areas for different constructions.

As with many optical stacks, control of the layer thickness is important to maintain product performance throughout long roll-to-roll production runs. In particular for display applications, control of the reflectance is key. With that in mind, the dependence of the reflection spectra with varying layer thickness was modeled for an Advanced Conductor stack with a SiOx layer between the PET and the Advanced Conductor. The thickness ranges studied were chosen to be roughly +/- 20% of the 25 and 50 nm thicknesses for the ITO and SiOx thicknesses, respectively. The additional SiOx layer was occasionally used to reduce resistance instabilities for certain systems. Figure 6 shows the results of these modeling studies with the spacer being the SiOx layer between the two ITO layers and the layer thicknesses in nm. The spacer layer thickness has a significant effect on the reflectance spectra with the reflectance minimum shifting to higher wavelengths as the spacer layer thickness increases. The actual minimum reflectance value is only slightly affected by the spacer layer thickness suggesting control of the spacer layer thickness is important for reflected color, not the amount. This agrees with the significant changes in b*determined from the modeling with spacer thickness shown in Figure 7. Trends with the bottom layer ITO thickness are opposite to those of the spacer layer in that the b* and the position of the reflectance minimum are relatively unaffected by the bottom ITO layer thickness while the amount of reflectance at the minimum varies drastically with changes in the layer thickness. The top ITO layer thickness significantly affects the position of the reflectance minimum and the amount of reflected b* (color) as well as the amount of minimum reflectance (intensity) with the wavelength of the reflectance minimum and the amount of reflectance at the minimum increasing with increasing layer thickness while b* decreases. While these variations in properties important to display performance are significant, they can be properly controlled through the use of in-line optical sensors and proper feedback controls.

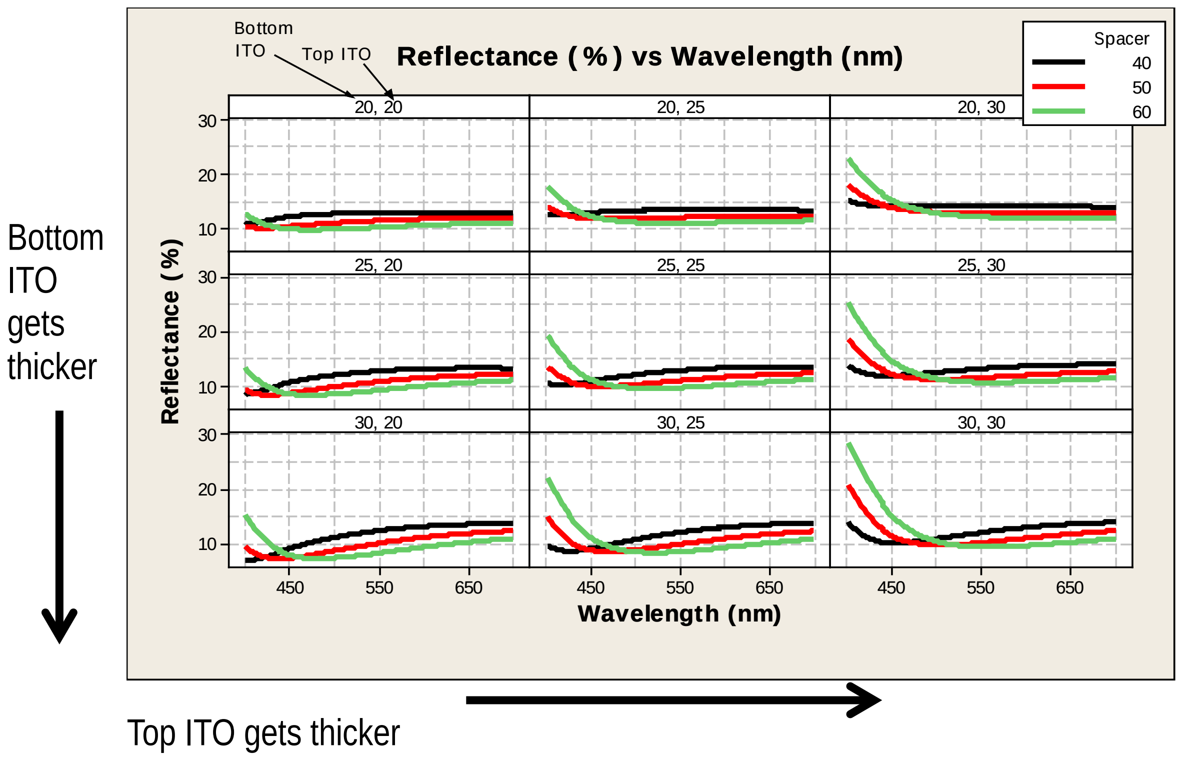


Figure 6. Reflectance of Advanced Conductor versus wavelength as ITO and SiOx spacer layer thicknesses are varied.

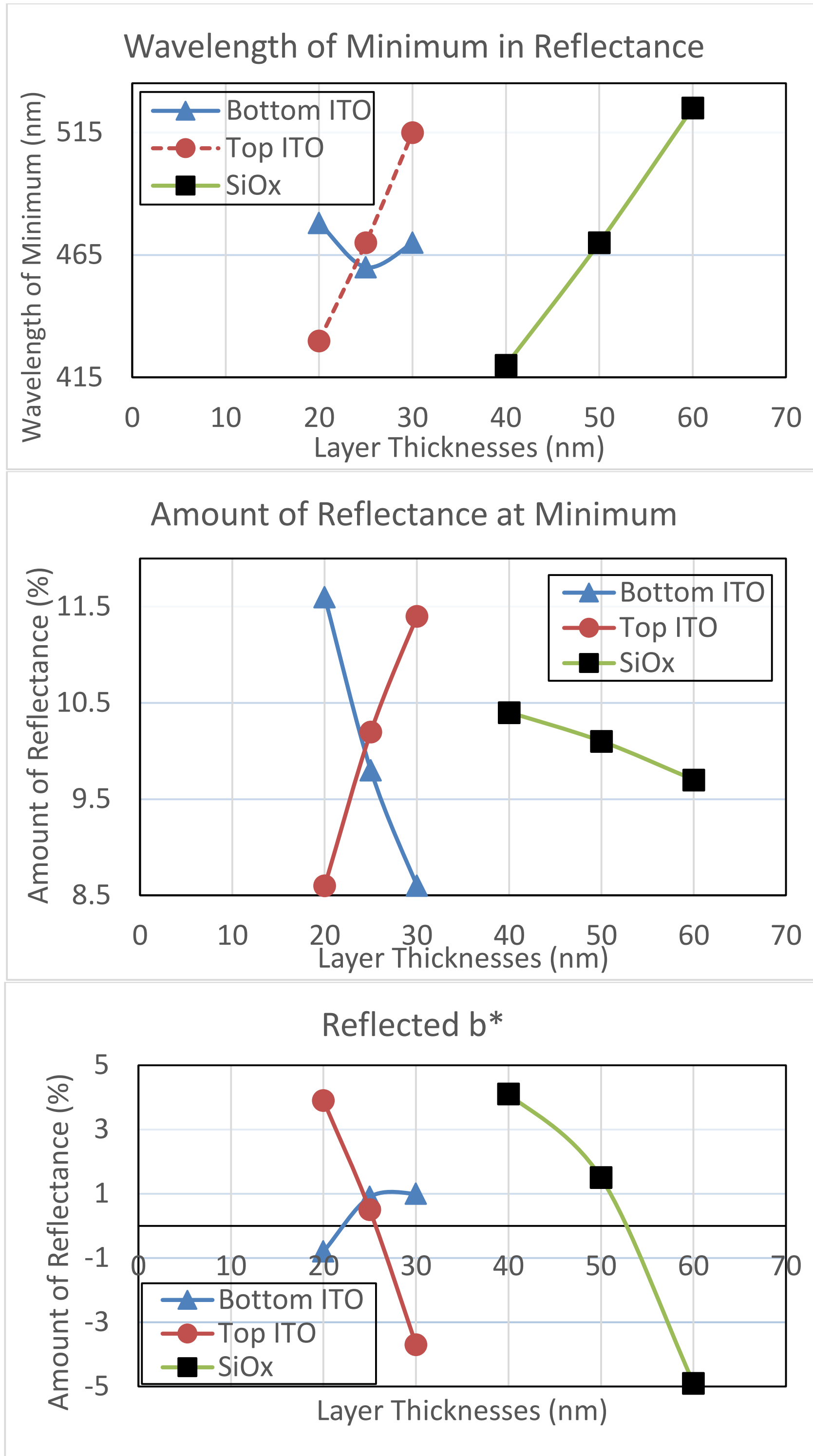


Figure 7. Sensitivity plots for reflectance values to layer thicknesses.

## 3M's Multi-Touch Displays

3M has applied the Advanced Conductor to its Projected Capacitive Technology (1) for displays through such products as the high-definition, high-contrast 22" and 32" Multi-Touch Displays, C2254PW and C3266PW, respectively (See Figure 8a below). With a durable glass touch screen surface, the 22" product has the ability to distinguish 20 touches at 6 millisecond touch response with more than 3300 touch sensing points in close proximity. With the demand for larger screen capabilities, in particular for table top applications, 3M marketed a C4667PW 46" Multi-touch display, shown in Figure 8b (2). Again featuring 3M's Projected Capacitive Technology (PCAP), this display handles up to 60 simultaneous touch events making it ideal for multi-user collaborative applications.

a) b)

Figure 8. 3M's a) 22" (C2254PW) and b) 46" (C4667PW) Multi-touch Displays.

## Summary

As a transparent conductor for multi-touch display applications, the 3M Advanced Conductor has several advantages over single layer ITO which include higher conductivities while achieving average transmission values greater than 90%. In addition, there is more of a neutral reflected color and less pattern recognition which can be further reduced through the use of a high n/low n layer stack between the Advanced Conductor and the PET substrate. 3M has used this technology to market a line of large area multitouch displays from a 22" to a 46" format.

## Acknowledgements

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