WELCOME TO THE WORLD OF ITO

From conventional LED to Mini & Micro LED or OLED on CMOS, the nature of ITO films and their interface with others plays a huge role in determining end device performance. Evatec specialists ***Hanspeter Friedli*** and ***Aikaterini Raftopoulou*** talk us through some of the film ITO properties which can be influenced through deposition conditions and how important it is to work in partnership with device manufacturers for developing an understanding of how each might be optimised for their own particular application.

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What ITO film properties can we vary?

Device manufacturers are continuously seeking to improve their overall device performance, typically through Forward Voltage (Vf) values which should be low and light outputs (LOP) which should be as high as possible. Here are some of the typical film properties we are have been asked to tailor for customers in the search for optimum ITO films and the results we have achieved so far.

Resistance

One of the most typical characteristics specified by customers is sheet or specific resistance which can be varied hugely according to the deposition process conditions chosen. These include RF/ DC ratio, oxygen flow and if deposition takes place cold or hot. The range of typical values we are often asked for is illustrated in the table below.

Achievements

Typical specific resistance values (after anneal):

for cold ITO	min: ~160μΩcm	up to max: ~400μΩcm or higher
for hot ITO	min: ~100μΩcm	up to max: ~400μΩcm or higher

Sheet resistance is also dependent on grain size, with typical results showing strong correlation for films with grain size less than 1 micron (see Figure 1).

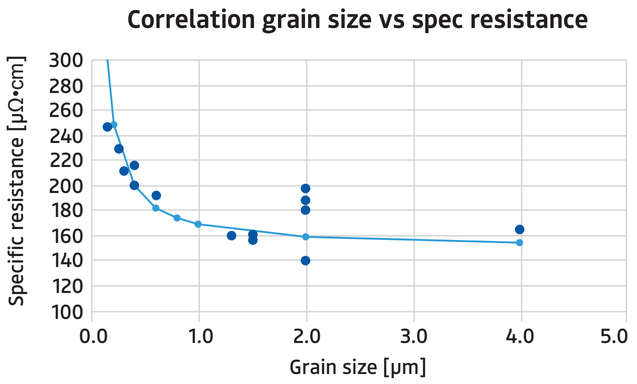


Figure 1: Specific resistance versus ITO film grain size

Achievements

Dependence resistance vs LOP

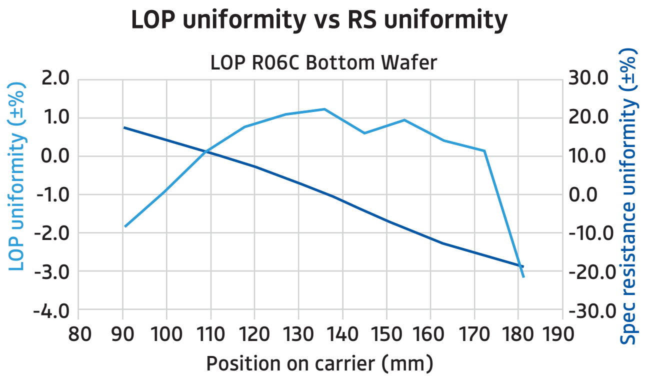


Figure 2: Relationship between resistance and LOP

When talking about ITO its important to remember that sheet resistance values refer to annealed films. Whenever we talk about specifications for sheet resistance we work together with customers to help them develop the widest possible process window by understanding their process flow – for example, whether anneal is done at the time of deposition of later on downsteam in their process.

Whilst ITO film resistance values may have an influence over other device performance criteria, we do know however from working together with customers that sheet resistance is not a tool we can use to modify Light Output Performance (LOP). In Figure 2, we can see LOP values plotted at different positions on a 200mm wafer and how film resistance values vary. There seems to be no correlation.

"We have more than 10 years experience in 'low damage' processes for ITO depostion"
Aikaterini Raftopoulou

Transmission

In general, we are looking for high transmission / low absorption films after anneal. Transmission values achievable vary considerably with both film thickness and the deposition conditions used. There are important dependencies between thickness uniformities and transmission. Some typical achievements are shown in the table below.

Every customer has different requirements, so it can be a trade off between what transmission values and thickness uniformity are acceptable. Again we like to work together with customers always thinking about the end properties required for annealed films. Using other variables like RF/ DC ratio or gas flows also helps us develop the widest possible process window. The transmission performance of some typical films is shown in figures 3a and 3b.

Achievements

Typical transmission values after anneal are: measured @ 450nm
for ~1100Å: > 98.5% with perfect thickness uniformity (< ± 0.6% on 6 inch)
for ~200Å: max ~98% with worse thickness uniformity (< ± 1.5% on 6 inch) max ~96.5% with better thickness uniformity (< ± 0.8% on 6 inch)

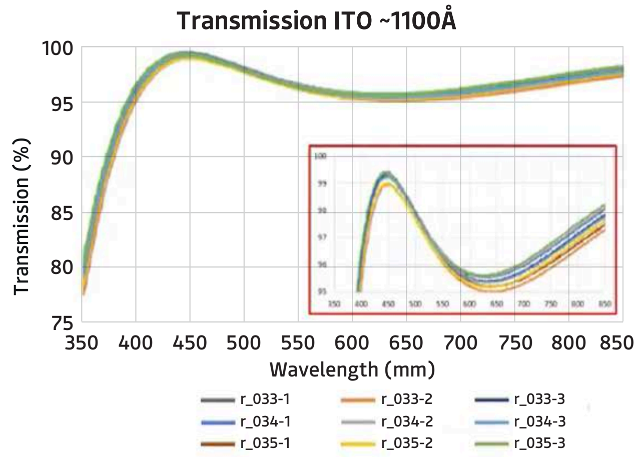


Figure 3a: Typical transmission performance for a thick ITO film

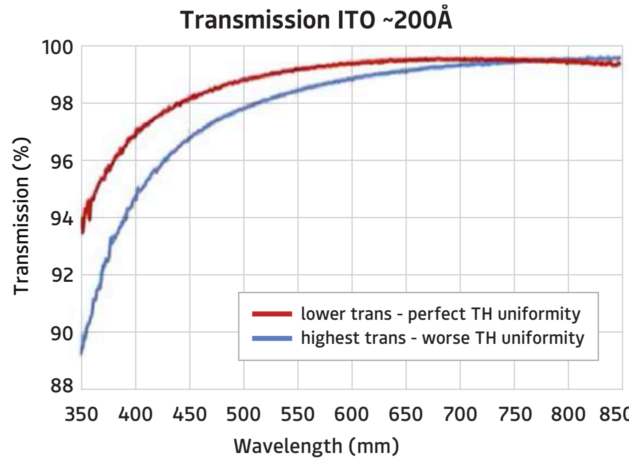


Figure 3b: Typical transmission perfromance for a thin ITO

Film Uniformity

Over the last years we have seen a trend to customers requiring both thin films in the range (150Å to 300Å) and thick films (1000Å to 3000Å), with very high uniformities in both cases. As you can imagine, measuring uniformities accurately for very thin films is challenging but you see some typical results that we have achieved on our high throughput CLUSTERLINE® 200 BPM tool where the use of rotating chucks is very helpful to achieve such good uniformities in figure 4. Optimising process conditions for film uniformity will certainly influence device performance properties like Vf or LOP but not always in a direction that we might first expect so we certainly need to optimise other process variables too to achieve the results our customers are looking for.

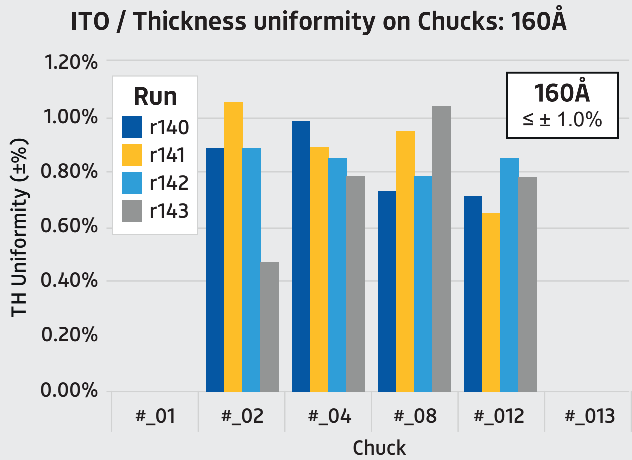


Figure 4a: Thickness uniformity for a thin film

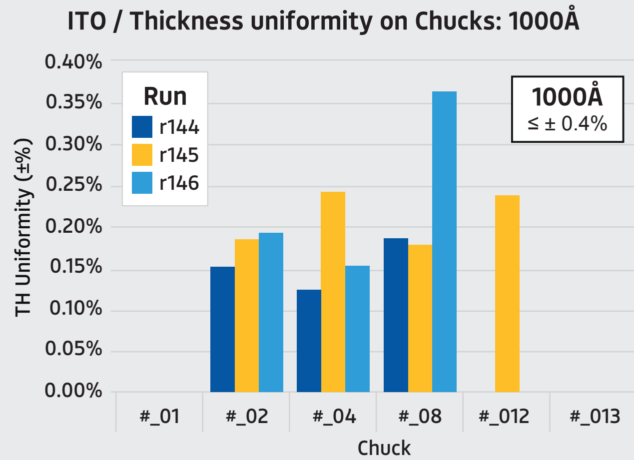


Figure 4b: Thickness uniformity for a thick film

Film Roughness

Typically our customers call for low roughness values. The micrographs in figure 5 show how changing deposition conditions like RF/ DC ratio for cold deposition of 300Å films has a large impact on grain size but almost no influence on Ra value which remains in the range 0.1 to 0.2nm.

For hot deposition however, we see its generally possible to deliver much higher variation of Ra values in the range 0.5 to 2nm. Varying conditions for hot deposition processes has been as an effective tool to achieve the specific film roughnesses requested by the some customers, but understanding the influence of film roughness values like Ra on device performance is certainly an area we are seeking to understand in more detail going forwards.

Depending on anneal conditions we can observe specific film features like needles occurring (see Figure 6). While such changes might not be picked up in Ra measurements, they would however have a strong influence on any measured Rz values, so it is also important to distinguish between different roughness parameters too.

While these can be controlled according to our choice of exact anneal conditions such as temperature and process gas this will in turn have an influence on device performance characteristics like Vf/ LOP.

Achievements

LOWEST roughness films are typically made as COLD deposition

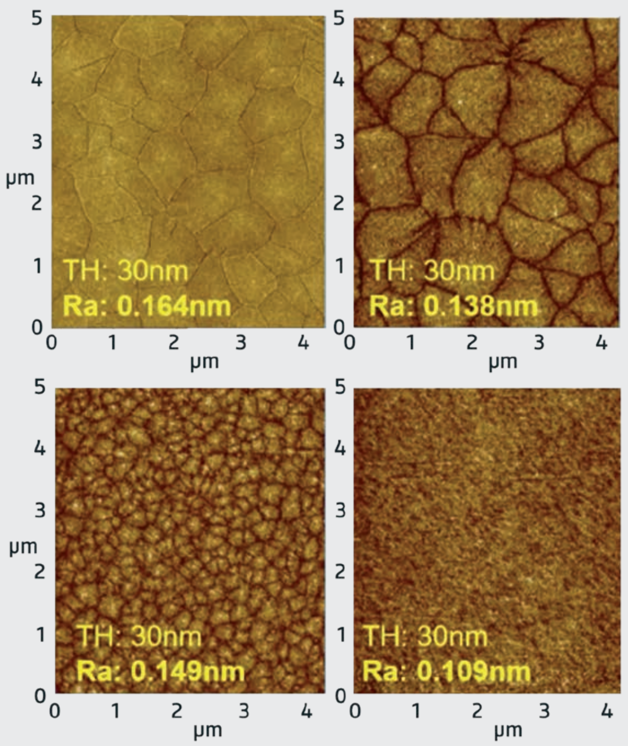


Figure 5: Films with very differing grain sizes can have very similar Ra values (note scan aresa 4x5µm)

> "Even after more than 20 years of working on ITO there is still so much to learn... and thats what makes it so exciting"
> **Hanspeter Friedli**

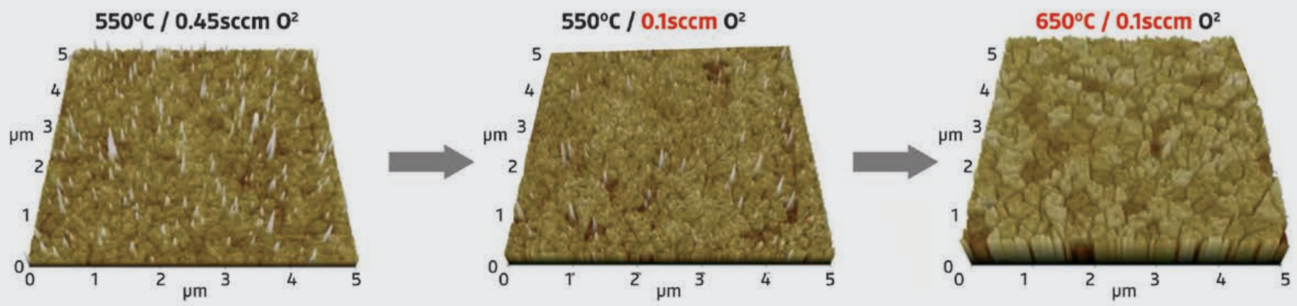
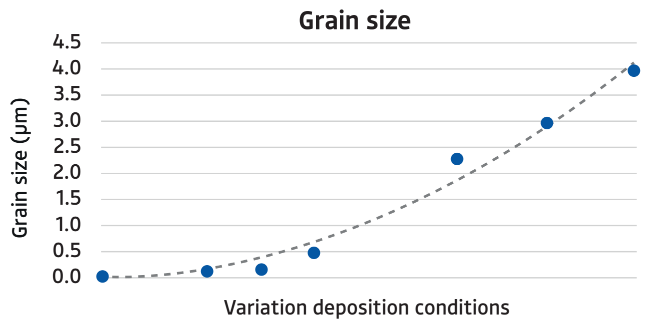


Figure 6: Influence of annealing conditions of film morphology.

Grain Size

Cold deposition processes tend to produce more rounded grains relative to hot deposition, but in both cases we have effective tools to control grain sizes from small to large.

Figure 7 shows how we can use our know-how to achieve film grain sizes that are optimal for each customer device.



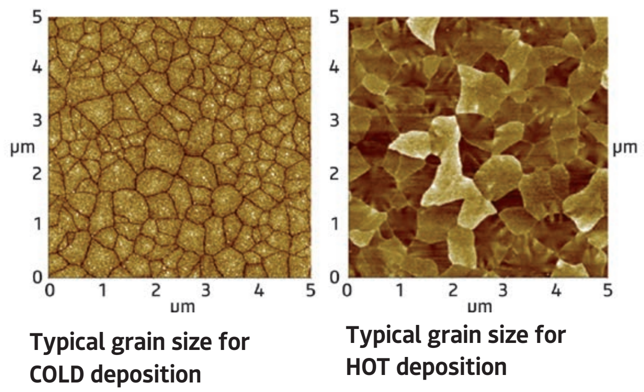


Figure 7: Effective management of grain size

Step coverage

For certain LED device designs with high aspect ratio "pilar" structures we also see a demand for achieving good step coverage on the side wall. Controlling a number of parameters including deposition geometries and process pressures has certainly given us results in an acceptable range so far but its still early days in our investigations.

How do we find the ultimate conditions?

It's complex... and its only by working closely together in detailed studies with device manufacturers that we can help them improve their device LOP and Vf values. Such studies may help us understand identify general trends for the influence of individual film parameters but one thing is clear... there is no perfect "one solution fits all" process. Every customer and every device architecture is different with different GaN properties. The optimum will also be different for bulk layer or contact layer processes, and how each customers' anneal processes differ, – e.g. what temperatures?, what gas flows?

Having said all that, through all the experience we have gained in the last 10 years its clear that we have a good handle on practical processes that work in production. We have a pretty good understanding of the process limits we can work within to maintain acceptable Vf values and we also have Best Known Methods (BKM) that are a great starting point.

Fine tuning these for customers is just part of our daily business

So what else are we working on?

Contact resistance of ITO films to EPI layer

It's a tricky parameter as it's not easy to measure but its certainly important.

In house computer simulations have already shown that contact resistance is a dominant factor influencing Vf and LOP. The cooperation with customers is highly important to measure the contact resistance on specific customer GaN. This close cooperation will ultimately lead to higher LOP and lower Vf.