Hybrid Printing of High Resolution Metal Mesh as Transparent Conductor for Touch Panel and OLED

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Abstract

A hybrid printing technique has been developed to manufacture high resolution metal mesh as flexible transparent conductors. The metal mesh structures are made by embedding silver nanoparticles inks into trenches which are patterned by high resolution nanoimprinting technology. Compared to other nanosilver type or metal mesh type of transparent conductors, the new technology can make much finer metal mesh (<3μm) with much higher conductivity (<1Ω/□) while still maintaining high transparency (>88%). The transparent conductor sheets can be roll-to-roll printed, which offers significant cost advantage over ITO electrodes. The new technology has been successfully implemented in high volume manufacturing of touch panel sensors for displays, as well as adapted to making flexible OLED.

Author Keywords

Transparent conductive films; ITO alternatives; Metal mesh

1. Introduction

Transparent conductive substrate is an essential component of touch panels and organic light emitting diode (OLED) devices. Indium tin oxide (ITO) has so far been the only choice of material for making the transparent conductors despite its high cost and high brittleness. With the globally escalating demands for touch screen displays and compounded with scarceness of indium mineral reserves, many alternatives to ITO for transparent conductive substrates are being developed, such as conductive polymers, carbon nanotubes, graphene, silver nanowires and metal mesh, etc. Among the many alternatives, metal mesh approach has emerged as the front runner, not only due to its lowest sheet resistance but also due to its relative ease to manufacture and relatively abundance of conductive materials. Figure 1 shows a comparison of surface conductivity versus manufacturing cost for different transparent conductive films [1].

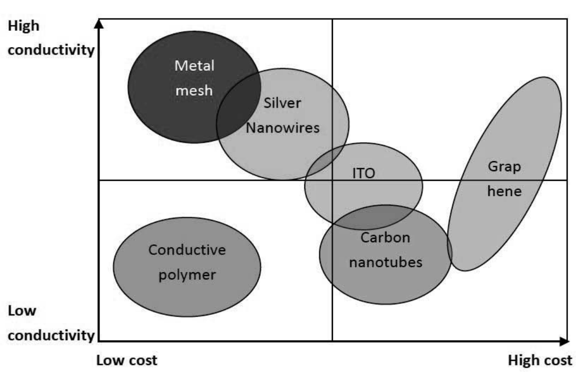


Fig.1 Comparison of metal mesh with other transparent conductive films [1]

There are different methods to make metal mesh type of transparent conductors, such as using coated silver nanowires, self-assembled silver nanoparticle inks, photolithographically patterned metal film, gravure or inkjet printed metal lines. Each of these methods has its own advantages and disadvantages. However, all the metal mesh transparent conductors must satisfy some key criterions in order to be usable in touch panel and OLED applications. These criterions are low sheet resistance, high transparency, low haze, good adhesion to substrate, simple manufacturing process, and most importantly, low cost comparing to existing ITO material. So far the reported approaches of metal mesh construction methods are only able to meet some of the criterions, which resulted in slow adaption of the technology in touch panel industry.

2. Technology

The metal mesh technology developed at the Suzhou Institute of Nanotech, Chinese Academy of Sciences, is based on a revolutionized hybrid printing technique which is able to satisfy all the aforementioned criterions for integrating the transparent conductors into a touch panel. Unlike many other approaches for making the metal mesh, the key feature of this hybrid printing technology is that the lines of mesh are made in trench form and the conductive materials, in this case the silver nanoparticles, are filled into the trenches. In this way, the conductive tracks are embedded into the substrate instead of laying on the surface. By employing the well known nanoimprinting technology, much finer and deeper trenches can be made. Figure 2 schematically illustrates the difference between normal printing and hybrid printing of metal inks into metal lines. The resulted metal meshes can achieve line width less than 3μm. With 1:1 of depth to width aspect ratio for the trench, the thickness of the silver nanoparticles filling is around 3μm as well. Figure 3 is the cross section of an embedded metal line. None of the existing metal mesh patterning techniques can make such thick metal lines on surface. With such a large amount of conductive material loading in metal mesh, transparent conductors with the sheet resistance of 0.69Ω/□ have been successfully fabricated.

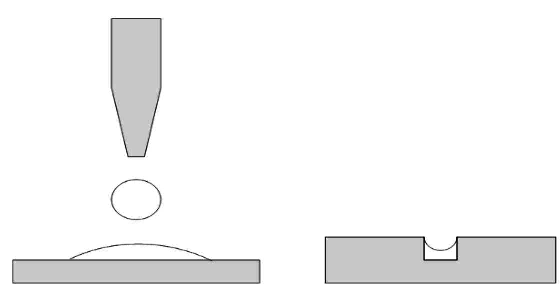


Fig.2 Normal inkjet printing (left) and hybrid printing (right) to make metal lines

 ISSN 0097-966X/15/4501-0398-$1.00

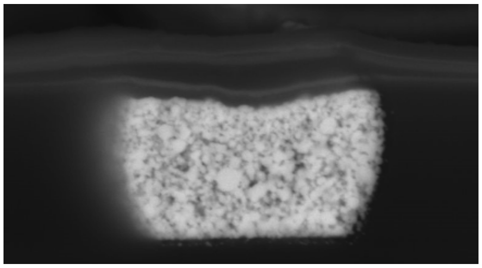


Fig.3 Cross-section of embedded metal line made by hybrid printing technique

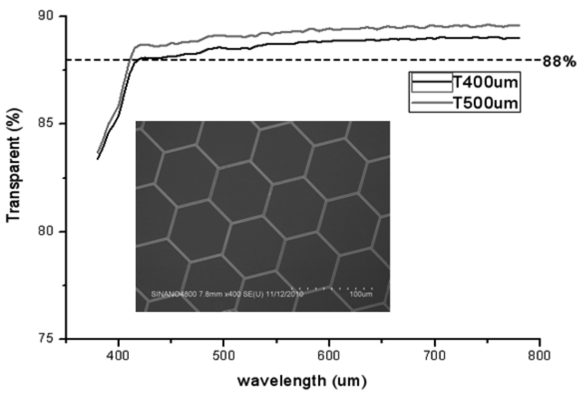


Fig.4 Dependence of transparency on the hole size of metal mesh (inset is the picture of metal mesh)

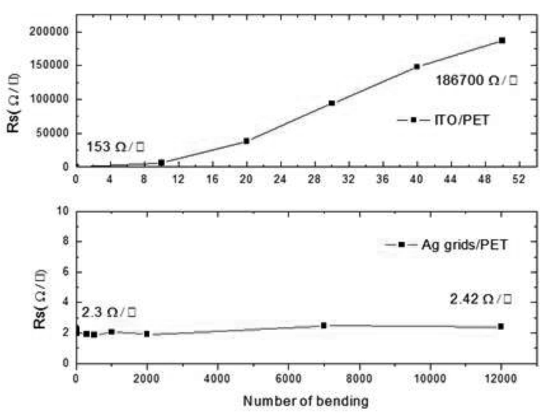


Fig.5 Flexibility test of embedded metal mesh transparent conductor in comparison to ITO (bending radius of 7mm)

All other transparent conductive films based on coating conductive materials, such as ITO, graphene, carbon nanotubes, silver nanowires and conductive polymers, have the conflict requirements for better surface conductivity and better transparency, i.e. higher surface conductivity requires thick coating of conductive materials which adversely reduces the transparency. Metal mesh type of transparent conductive film does not have this issue because the conductivity is achieved by metal lines whereas the transparency is insured by mesh holes. Higher transparency can be achieved by large mesh holes, as indicated in Figure 4 where different sizes of mesh holes have different transparency. The present hybrid printing technique is able to achieve high transparency without sacrificing the surface conductivity because more conductive materials can be embedded into a deeper trench without enlarging the width of trench. The embedded metal mesh is also of high flexibility, as tested in Figure 5 where the flexibility of ITO on PET substrate is compared.

There have been criticisms on metal mesh transparent conductors when they are applied to touch sensors and display applications, such as the metallic mesh lines are visible, the haze is high and there is an electric breakdown issue due to electromigration of silver atoms., etc. The present innovative approach has solved all the above issues. The mesh line below 5μm width become invisible to naked eyes. The haze is considerably reduced because of the embedded structure of metal lines. In addition, a blackening treatment to the metal mesh can further reduce its haze and reflective flare problems. Figure 6 compares the metal mesh before and after blackening treatment. The reflective flare has been completely eliminated and the haze can be reduced to less than 1%. As for the eletromigration issue, embedding silver nanoparticles into a deep trench can greatly deter the migration of silver atoms.

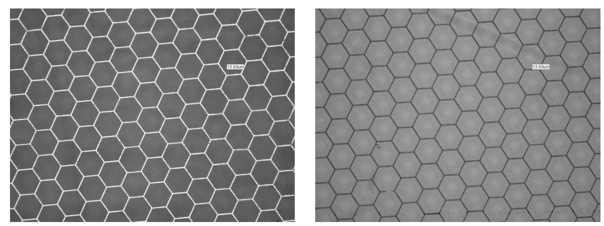


Fig.6 Metal mesh before blackening (left) and after blackening (right) treatment

The most important advantage of the new approach is that the hybrid printing process can be done in roll-to-roll fashion, which enables high throughput manufacturing and significant reduction of cost. Conventional touch panel manufacturing normally involves three separate processes: coating of conductive materials to make transparent conductive films (TCF), patterning of touch electrodes by photolithography and metal etching, screen printing of border electrodes. The new hybrid printing approach can combine the above three processes into one continuous roll-to-roll step, including imprinting of trenches and filling of conductive materials. Because the trenches are made by a template which can be designed with any patterns including both touch electrodes and border connection electrodes, the printed final films are not just TCFs but complete touch sensor films ready to assemble into touch panels. Figure 7 shows a roll of printed transparent conductive films which already contain the complete design of touch panels.

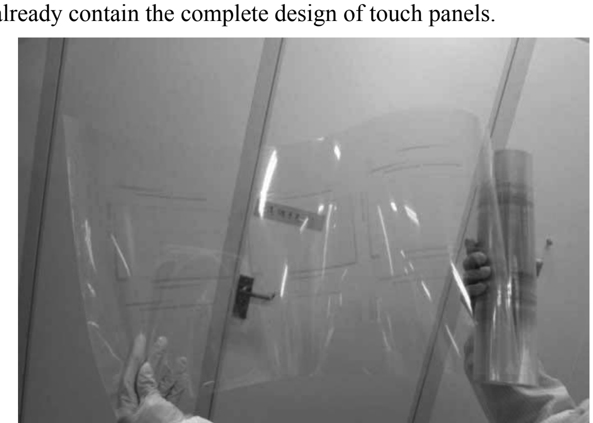


Fig.7 Roll of printed transparent conductive film with touch panel designs

3. Applications

3.1 Touch panels

The aforementioned hybrid printing of metal mesh transparent conductive films has been implemented in high volume manufacturing at the Nanchang O-Film Display Technology. Co. Ltd., China, which is the largest touch panel manufacturer in the world. Currently, O-film can produce half million medium or large size metal mesh touch panels per month. Figure 8 shows the roll-to-roll printing of touch panel film at O-film.

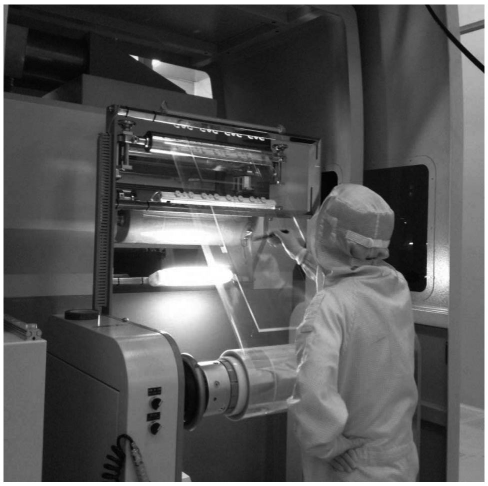
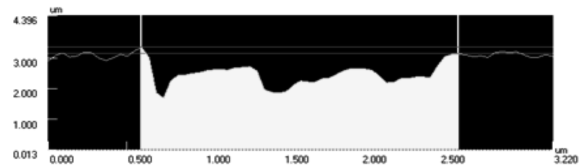


Fig.8 Roll-to-roll printing of touch panel film

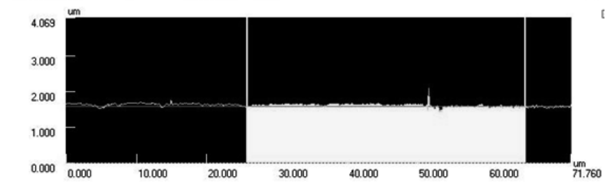
Because of its very high surface conductivity, the film is particularly advantageous for large size of touch panel. For a 24 inch touch panel, the cross-panel resistance is measured at 20kΩ if the touch sensor film is made of ITO, the hybrid printed metal mesh touch sensor film can reduce the cross-panel resistance to 1kΩ, which has greatly boosted the touch sensitivity to large size touch panels. The touch panels manufactured with the new hybrid printing technology at O-film have been commercialized and penetrated into mainstream notebook computers market.

3.2 OLED

Transparent conductors are not only widely used for touch panels but also for OLED lighting and display. Though transparent and conductive are the essential requirements for the electrodes in OLED, the surface flatness is also a critical parameter, because the light emitting layers in an OLED are only a few tenths of nanometers. Excessive roughness on the transparent electrode surface would short circuit the cathode and anode of an OLED. A metal mesh based transparent conductor has to be extremely flat, which is difficult to achieve if the metal lines are lying on surface. With the new hybrid printing approach, surface flatness is relatively easy to achieve, because the filling of conductive materials in trenches can be leveled to the surface. With additional polishing process, highly flat and smooth surface has been achieved as shown in Figure 9 where the surface roughness of partially filled and completely filled trenches are compared. The surface roughness can be reduced to around 10nm which is adequate to make OLED on it.



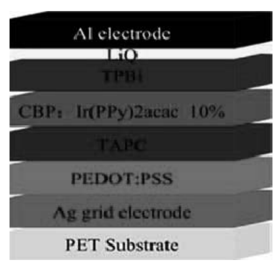
(a) Partially filled trench



(b) Completely filled and smoothed trench

Fig. 9 Comparison of surface roughness of metal filled trenches

With the improved the surface flatness, flexible OLEDs have been made using the metal mesh transparent conductor to replace ITO. Figure 10(a) shows the schematic layer structure of OLED and Figure10(b) shows the uniformly illuminating OLED.



(a) (b)

Fig.10 (a) OLED layer structure (b) illumination of OLED with metal mesh as the transparent conductor

4. Summary

A new hybrid printing technique has been developed to make metal mesh transparent conductors. The metal mesh is fabricated not on the surface of a transparent substrate but embedded into the substrate. Compared to ITO or all other ITO alternatives, the metal mesh transparent conductor has the lowest sheet resistance of 0.69Ω/□ while still maintaining 88% of transparency. The hybrid printing process can be implemented in roll-to-roll fashion, which can produce not just transparent conductive films but complete touch panels. High volume manufacturing of metal mesh touch panels has been realized at O-film and the non-ITO touch panels have been commercialized. The feasibility of utilizing the metal mesh transparent conductor in OLED has also been proved.

5. References

[1] "ITO-replacement: non-ITO transparent conductor technologies, supply chain and market forecast report", Touch Display Research, May 2013Journal of Physiology **252**, 627-656 (1975).