# A review of technologies for sensing contact location on the surface of a display

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***Abstract —*** Touchscreen interactive devices have become increasingly important in both consumer and commercial applications. This paper provides a broad overview of all touchscreen technologies in use today, organized into 13 categories with 38 variations. The 13 categories are projected capacitive, analog resistive, surface capacitive, surface acoustic wave, infrared, camera-based optical, liquid crystal display in-cell, bending wave, force sensing, planar scatter detection, vision-based, electromagnetic resonance, and combinations of technologies. The information provided on each touchscreen technology includes a little history, some basic theory of operation, the most common applications, the key advantages and disadvantages, a few current issues or trends, and the author's opinion of the future outlook for the technology. Because of its dominance, this paper begins with projected capacitive; more information is provided on this technology than on any of the other touch technologies that are discussed. This paper covers only technologies that operate by contact with a display screen; this excludes technologies such as 3D gesture recognition, touch on opaque devices such as interactive whiteboards, and proximity sensing. This is not a highly technical paper; it sacrifices depth of information on any one technology for breadth of information on multiple technologies.

***Keywords*** — touch technologies; touchscreen; touch panel; projected capacitive; in-cell; on-cell.

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## 1 Introduction

Touchscreen interactive devices have become increasingly important in both consumer and commercial applications, with over one billion touchscreens shipped in 2011.[1] This paper provides a broad overview of all touchscreen technologies in use today, organized into 13 categories with a total of 38 variations. The information provided on each touch technology includes a little history, some basic theory of operation, the most common applications, the key advantages and disadvantages, a few current issues or trends, and the author's opinion of the future outlook for the technology. This paper covers only technologies that operate by contact with a display screen; this excludes technologies such as three-dimensional (3D) gesture recognition, touch on opaque devices such as interactive whiteboards, and proximity sensing. This is not a highly technical paper; it sacrifices depth of technical information on any one technology for breadth of information on multiple technologies. In this paper (and throughout this issue of Journal of the Society for Information Display), the terms "touchscreen" and "touch panel" are synonymous; both refer to a module consisting of a touch sensor and a touch controller (the former term is more commonly used in the West, whereas the latter term is more commonly used in Asia). Also in this paper, projected capacitive touch technology is often abbreviated as "p-cap." The touch industry has not yet settled on a single term for p-cap technology; it is also called "Pro-Cap," "PCT" (p-cap touch [or] technology), and increasingly, just "capacitive," as surface-capacitive technology becomes ever less relevant.

## 1.1 Context

As shown in Fig. 1, analog resistive and p-cap touch technologies dominate the touch landscape today. Together they accounted for more than 80% of revenue and 95% of units shipped in 2011. Resistive was historically always the largest technology in both revenue and units, but p-cap overtook resistive in revenue in 2010 and in units in 2011 [1]. Because of this dominance, this paper begins with p-cap; more information is provided on this technology than on any of the other touch technologies that are discussed.

## 2 Projected capacitive (p-cap)

Worldwide sales of p-cap were less than \$20m in 2006, growing to over \$7b in 2011. More than 95% of the \$7b was in the consumer electronics market, with more than 75% in smartphones and tablets. Contrary to popular belief, Apple did not invent p-cap (or multi-touch!). The history of p-cap is less clear than that of many other touch technologies. The basic concept of sensing touch by measuring a change in capacitance has been known since at least the 1960s. In fact, the first transparent touchscreen, invented in 1965 for use on air-traffic system-control terminals in the UK, used a form of capacitive sensing.[2] Surface-capacitance touch technology (with an unpatterned sensor) was commercialized by MicroTouch Systems around 1985. During the mid-1990s, several US companies developed transparent capacitive touchscreens

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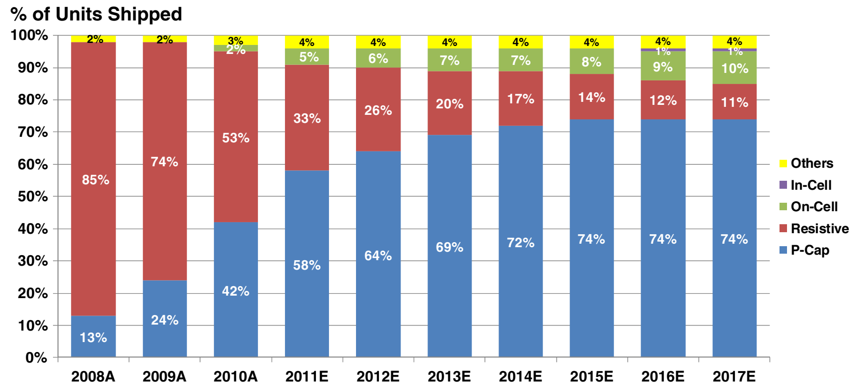

**FIGURE 1** — The touch world is already well into a transition from analog resistive (red) to projected capacitive (blue) as the dominant touch technology. The figure combines the opinions of an Asian investment bank (Guoxin Securities), the world's largest touchscreen supplier (TPK) and world's number one touch market research firm (DisplaySearch). Source: Guoxin Securities, TPK, and DisplaySearch.

with patterned sensors by using indium tin oxide (ITO, the foundation of today's p-cap). Two of these were Dynapro Thin Films and MicroTouch Systems; both of which were later acquired by 3M (in 2000 and 2001, respectively) to form 3M Touch Systems. Dynapro Thin Films' p-cap touchscreen technology, known as "Near-Field Imaging," became 3M's first p-cap product in 2001. Also in 1994, an individual inventor in the UK named Ronald Peter Binstead developed a form of p-cap by using microfine (25 micron) wire as the sensing electrode.[3] He licensed the technology to two UK companies: Zytronic in 1998 and Visual Planet in 2003; both are still selling it today.

P-cap remained a little-known niche technology until Apple used it in the first iPhone in 2007. Apple's engaging and immersive user interface was an instant hit, causing most other smartphone manufacturers to immediately adopt the technology. Over the next 5 years, p-cap sets a new standard for the desirable characteristics of touch in the minds of more than one billion consumers, as follows:

- Multiple simultaneous touches ("multi-touch" for zoom)
- Extremely light touch with flick/swipe gestures (no pressure required)
- Flush touch surface ("zero bezel")
- Excellent optical performance
- Extremely smooth and fast scrolling
- Reliable and durable
- Fully integrated into the device user experience so that using it is effortless and fun

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## 2.1 P-cap fundamentals

There are two basic kinds of p-cap: self-capacitance and mutual capacitance. Both are illustrated in Fig. 2. Self-capacitance is based on measuring the capacitance of a "single" electrode with respect to ground. When a finger is near the electrode, the capacitance of the human body increases the self-capacitance of the electrode with respect to ground. In contrast, mutual capacitance is based on measuring the capacitance between a "pair" of electrodes. When a finger is near the pair of electrodes, the capacitance of the human body to ground "steals" some of the charge between two electrodes, thus reducing the capacitance between the electrodes.[4]

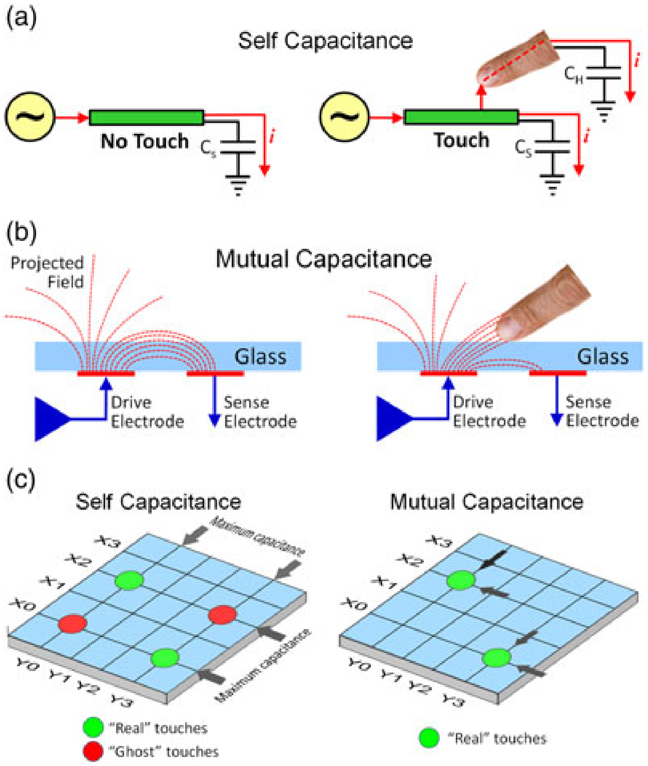

**FIGURE 2** — Self-capacitance (a) is the capacitance of a single electrode to ground. When a finger is near the electrode, human body capacitance to ground "increases" the total self-capacitance of the electrode. Mutual capacitance (b) is the capacitance between two electrodes. When a finger is near the electrodes, it "steals" some charge from the drive electrode, "reducing" the mutual capacitance between the two electrodes. In an X–Y self-capacitance grid (c, left), each row and column electrode is scanned individually. If the sensor is touched with two fingers that are diagonally separated, the controller sees two maximums on each axis, but cannot tell which pair of maximums is the real touch points. In an X–Y mutual-capacitance grid (c, right), each electrode intersection is scanned individually, allowing multiple touch points to be unambiguously identified. Source: 3M and Touch International; redrawn by the author.

Although it seems that the difference between self and mutual capacitance could be determined by the number of electrodes, the key difference is actually in how the electrodes are measured. Regardless of how they are configured, the electrodes in a self-capacitance touchscreen are measured individually, one at a time. For example, even if the electrodes are configured in a two-layer X–Y matrix, all the X-electrodes are measured, and then all the Y-electrodes are measured in sequence. If a single finger is touching the screen, the result is that the nearest X-electrode and the nearest Y-electrode will both be detected as having maximum capacitance. However, as shown in Fig. 2(c), if the screen is touched with two or more fingers that are diagonally separated, there will be multiple maximums on each axis, and "ghost" touch points will be detected as well as "real" touch points (ghost points are false touches positionally related to real touches). Note that this disadvantage does not eliminate the possibility of using two-finger gestures on a self-capacitive touchscreen. Rather than using the ambiguous "location" of the reported points, software can use the "direction of movement" of the points. In this situation, it does not matter that four points resulted from two touches; as long as pairs are moving toward or away from each other (for example), a zoom gesture can be recognized. For this reason and because self-capacitance can be of lower cost than mutual capacitance, the former is often used on lower-capability mobile phones.

In contrast, in a mutual-capacitive touchscreen, each electrode "intersection" is measured individually. Generally, this is accomplished by driving a single X-electrode, measuring each Y (intersecting) electrode, and then repeating the process until all the X-electrodes have been driven. This measurement methodology allows the controller to unambiguously identify every touch point on the touchscreen. Because of its ability to correctly process multiple touch points (moving or not), mutual capacitance is used in preference to self-capacitance in most smartphones and tablets today.

## 2.2 P-cap controllers

In every case, the measurement of electrode capacitance is accomplished by a touch controller. Figure 3 illustrates the basic structure of a controller for a mutual-capacitance touchscreen. A sensor driver excites each X-electrode one at a time. An analog front-end measures the capacitance at the intersection of each Y-electrode and the excited X-electrode; the analog values are converted to digital by an analog-to-digital converter. A digital signal processor runs highly sophisticated algorithms to process the array of digital capacitance data and convert it into touch locations and areas, along with a variety of related processing such as "grip suppression" (the elimination of undesired touches near the edge of the screen resulting from holding a device) and "palm rejection" (the elimination of unintended touches resulting from the edge or base of your palm contacting the screen in the process of touching with a finger). A p-cap touch controller is an example of an application-specific integrated circuit (ASIC).[5]

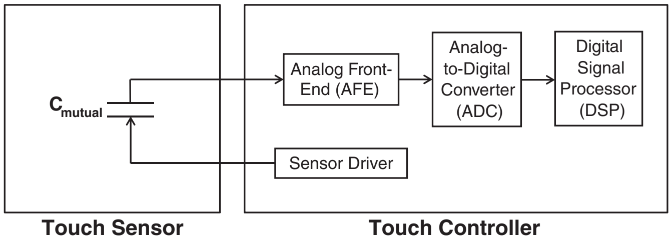

**FIGURE 3** — A projected capacitive touch controller consists of only four main elements: a sensor driver to excite the drive electrodes, an analog front-end (AFE) to read the sense electrodes, an analog-to-digital converter (ADC), and a digital signal processor (DSP). Source: Maxim Integrated Products.

Controllers are where most of the innovation is happening in p-cap today, although the geometry of the sensor pattern is also an ongoing contributor to performance improvement. The top three controller suppliers (Atmel, Cypress, and Synaptics, who together accounted for more than half of the p-cap controller unit shipments in 2011) are all US-based companies.[6] This could be taken as a sign of the relative youth of the p-cap controller industry because most system-level ASICs eventually become commoditized with suppliers based in Asia. An example of recent p-cap controller innovation is the significant increase in touch system signal-to-noise ratio (SNR) that has occurred during the last 18 months. The value of this innovation is that is allows p-cap touchscreens to support an active or passive stylus with a 1-mm tip, rather than just a human finger. Multiple p-cap controller suppliers have demonstrated or talked about this capability with regard to their latest controllers, although there has not been enough time for it to show up in consumer electronic products on the shelf yet.[4,7]

A fine-tipped stylus adds a large amount of value to a smartphone or tablet. It allows the user to "create" data (drawings, notes, etc.) rather than just "consume" media. In Asia, it is highly desirable to write Kanji characters on a smartphone, and finger writing is impractical because the tip of your finger obscures what you are writing. A fine-tipped stylus is also excellent as a pointing device for use with software that was not designed for touch (e.g., legacy Windows applications running on a Windows 8 tablet in "desktop" mode).

## 2.3 P-cap sensors

A p-cap sensor is at heart a set of transparent conductive electrodes used by the controller to determine touch locations. In self-capacitance touchscreens, transparent conductors are patterned into spatially separated electrodes in either a single layer or two layers. When the electrodes are in a single layer, each electrode represents a different touch coordinate pair and is connected individually to a controller. When the electrodes are in two layers, they are usually arranged in a layer of rows and a layer of columns. The intersection of each row and column represents unique touch coordinate pairs; however, as noted in the previous section, in self-capacitance, each electrode is measured individually rather than measuring each intersection with other electrodes, so the multi-touch capability of this configuration is limited.

In a mutual-capacitance touchscreen, there are almost always two sets of spatially separated electrodes. In higher-performance touchscreens (such as that in the iPhone), the electrodes are usually arranged in a rectilinear grid of rows and columns, spatially separated by an insulating layer or a film or glass substrate. In contrast, the most commonly used electrode pattern is an interlocking diamond consisting of squares on a 45° angle, connected at two corners via a small bridge. When this pattern is used on two spatially separated layers, the processing of each layer is straightforward. However, this pattern is often applied in a single "coplanar" layer to achieve the thinnest possible touchscreen. In this case, the bridges require additional processing steps to (1) insulate the first ITO bridge before depositing the second (intersecting) ITO bridge or (2) omit the second ITO bridge during deposition and replace it with a metal "microcrossover" bridge.

Figure 4 illustrates the stack-up of a typical mutual-capacitance touchscreen. To keep this and all similar drawings in this paper as easy to understand as possible, several simplifications have been made, as follows. (1) The electrode pattern shown (rows 3 and 5) is a rectilinear grid rather than the more common interlocking diamond; row 3 shows the end views of the Y-electrodes, whereas row 5 shows a side view of one X-electrode. (2) The common use of optically clear adhesive has been omitted; for example, the space between rows 2 and 3 is typically filled with optically clear adhesive. (3) The touchscreen is shown using a glass substrate; in lower-end mobile phones, the substrate is often two layers of polyethylene terephthalate (PET) film, one for each set of electrodes. (4) All the layers below the thin film transistor (TFT)-array glass in the liquid crystal display (LCD) (e.g., bottom polarizer, brightness enhancement films, and backlight) have been omitted.

One of the key points made in Fig. 4 is that the touchscreen adds a fourth sheet of glass to the stack-up. All LCDs use two sheets of glass, and essentially, every mobile device adds a third sheet of glass (or Poly(methyl methacrylate) (PMMA)) as a protective and decorative covering over the LCD. Adding a fourth sheet of glass is generally considered to be undesirable because it adds weight, thickness, and cost to the mobile device. There are two basic methods of eliminating the fourth sheet of glass: (1) the method used by the touchscreen industry, called "one-glass solution," "sensor on lens," or a variety of company-specific names, and (2) the method used by the LCD industry, called "on-cell touch." These methods are in direct competition.

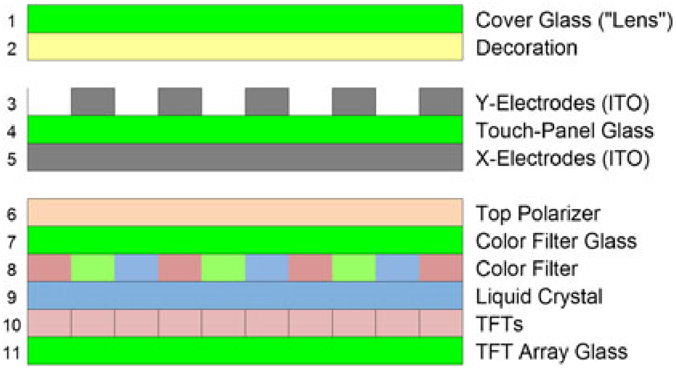

**FIGURE 4** — All smartphones and tablets use some form of "decorated covering" (rows 1 and 2) to protect the LCD (rows 6–11) from damage. When a projected capacitive touchscreen is added, most commonly, the electrodes are located on a fourth piece of glass (rows 3–5). ITO, indium tin oxide; TFT, thin film transistor. Source: the author.

Figure 5 illustrates the one-glass solution, in which the touchscreen electrodes are moved to the underside of the decorated cover glass ("lens").[8] In this solution, the touchscreen manufacturer either purchases the decorated cover glass from an appropriate supplier or vertically integrates and acquires the equipment and skills necessary to manufacture the cover glass. The touchscreen manufacturer then builds the touch module (sensor plus controller) by using the decorated cover glass as a substrate and sells the entire assembly to a mobile device Original Equipment Manufacturer/Original Design Manufacturer (OEM/ODM) (as is often the case, the touchscreen manufacturer may also obtain the LCD on consignment from the device OEM/ODM and integrate the touchscreen module with the LCD). The advantage of the one-glass solution to the end user is that the mobile device is lighter and thinner because of the elimination of the fourth piece of glass. The advantage of the one-glass solution to the touchscreen manufacturer is that they continue to derive revenue from the production of touchscreens instead of forfeiting revenue to the LCD industry.

Figure 6 illustrates the on-cell touch solution, in which the fourth piece of glass is eliminated by moving the touchscreen

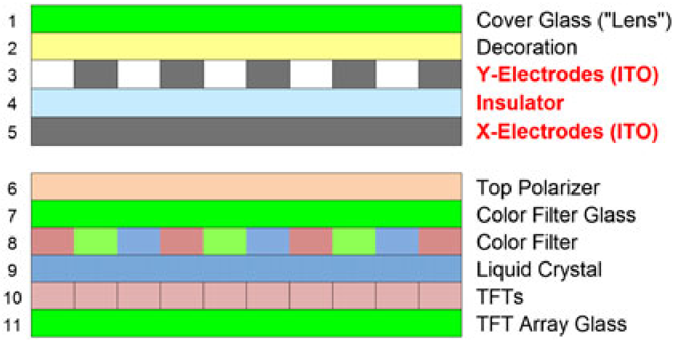

**FIGURE 5** — This figure depicts the p-cap "one-glass solution" (also called "sensor on lens") configuration used by the touchscreen industry. To eliminate the fourth piece of glass, the p-cap electrodes are moved to the bottom surface of the decorated cover glass (rows 3–5). ITO, indium tin oxide; TFT, thin film transistor. Source: the author.

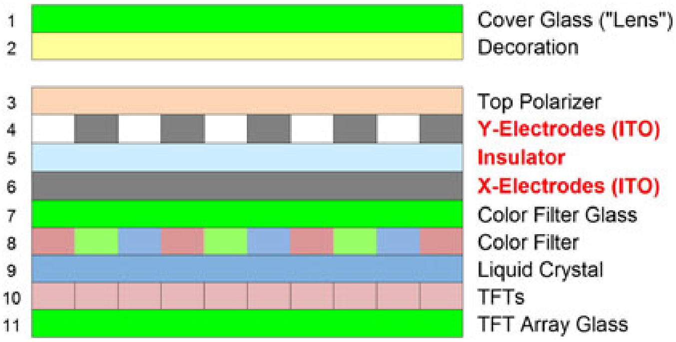

**FIGURE 6** — In the on-cell touch sensor configuration used by the liquid crystal display industry, the fourth piece of glass is eliminated by moving the p-cap electrodes to the top of the color filter glass, underneath the top polarizer (rows 4–6). The touch functionality is exactly the same as in Figure 5. ITO, indium tin oxide; TFT, thin film transistor. Source: the author.

electrodes to the top of the color filter glass, underneath the LCD's top polarizer. Note that an on-cell configuration is standard p-cap with exactly the same functionality as in Figs. 3 and 4; only the location of the electrodes is different. The advantage of the on-cell solution to the end user is exactly the same as the one-glass solution—the mobile device is lighter and thinner because of the elimination of the fourth piece of glass. The advantage of the on-cell solution to the LCD manufacturer is that it increases their revenue because of the added value of touch functionality (but the touchscreen manufacturer loses revenue).

One other factor in on-cell's favor is that with the touch sensor integrated into the LCD, it makes sense to consider integrating the touch controller and the display driver together into a single ASIC or at least establishing a direct connection between the two chips to enable cooperation. Manufacturing yield can be more of an issue with on-cell because depositing the electrodes on the top surface of the color filter glass substantially increases the value of that one piece of glass; if either the color filter or the touch electrode deposition is defective, both must be discarded. Product-line management is also an issue for the LCD manufacturer—for example, should every LCD be designed with on-cell touch included or only some models? Should there be two versions of a high-volume LCD, one with on-cell and one without?

It should be clear from the aforementioned that on-cell touch is not necessarily an automatically better solution than one-glass. There are factors to be considered on both sides, and some of those factors are more business-related and operational-related than technical. Competition between touch module manufacturers and LCD manufacturers will remain a major factor in the progression of on-cell. The author believes that on-cell will achieve only limited success in the next 5 years, accounting for no more than 10%–15% of all p-cap touch in consumer electronics applications and much less (if any) in commercial applications.

## 2.4 ITO-replacement materials for p-cap sensors

ITO-replacement materials eliminate the need for vacuum sputtering; patterning of ITO-replacement materials can be carried out at room temperature in a normal atmosphere without the need for an expensive fab. This is potentially a highly disruptive technology.

Because of the fine resolution required in creating the pattern (e.g., 20-micron-wide ITO conductors) and the relatively large number of electrode connections that must fit in a very narrow space at the edge of the touchscreen, most glass-based sensors are patterned using photolithography on a fabrication plant ("fab"). There are three basic sources of fabs: (1) converted from LCD color filter fabs, (2) converted from passive LCD fabs, and (3) purpose built. Existing p-cap fabs were expanded at a very rapid rate in 2011; the author estimates that the total capital expenditures ("capex") spent by the p-cap touch industry in 2011 was around $2b. The necessity of creating the sensor on a fab contributes substantially to the high cost of a p-cap touchscreen today. For example, a glass touchscreen module for a 10-in Android tablet in high volume currently costs the device OEM/ODM around $25 for the sensor, whereas the controller is typically under $5 (this does not include the cost of the cover glass and lamination).

There are at least five different materials competing to become the dominant ITO-replacement material, including copper metal mesh, silver nanowires, carbon nanotubes, conductive polymers, and ITO inks. In the author's opinion, the material with the most market traction so far is metal mesh. Two examples of companies working with metal mesh include Atmel and Unipixel. Atmel recently announced their XSense™ sensor film; it uses a metal mesh printed roll-to-roll on film.[9] Atmel's partner for the mesh and printing equipment is Conductive Inks Technology in the UK. Because the transparent conductor is metal, the material's sheet resistance is very low (less than 10 ohms/square and in some cases, as low as 0.6 ohms/square). This provides increased noise immunity and helps support both active and passive styli. Unipixel has been working for several years on its UniBoss copper metal mesh with a conductor size of 5 microns (invisible). The mesh can be printed roll-to-roll in a single pass at room temperature; Unipixel appears to be nearing production readiness.[10] In fact, scuttlebutt within the touch industry in June 2012 indicates that Unipixel is already providing (under NDA) small quantities of metal mesh for production of 32-in p-cap touchscreens.

Silver nanowires are a close second behind metal mesh. The leading supplier of this material is Cambrios; the optical and electrical properties (transmissivity and sheet resistance) of Cambrios' material are highly competitive with ITO. The material has been used by Synaptics in the first non-ITO p-cap touchscreen used in a smartphone (Samsung's CricKet™ brand, sold only in Asia).[11] This is much more important than it may seem; it is the beginning of direct competition for capital-intensive, high-cost p-cap sensor manufacturing.

3M is an example of a company working with both silver nanowires and metal mesh. 3M is planning to combine their well-known microreplication process with a solution-processable metal mesh or silver-nanowire material to create roll-to-roll printed p-cap sensors on film that can be laminated to glass. A joint venture between 3M and Quanta has been launched in Singapore to market 3M's p-cap sensors to the consumer electronics OEM/ODM manufacturing tablet and larger products (but not smartphones).[12]

The author believes that within 5 years, metal mesh and/or silver nanowires will be used in up to half of all tablet-sized and larger p-cap sensors because it will substantially reduce the cost of sensor production. This will put intense pressure on the owners of p-cap fabs, particularly those who specialize in larger touchscreens. If they cannot compete, many of those p-cap fabs will either become idle or be converted to some other use—similar to what happened to passive LCD fabs when TFT LCDs became dominant.

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