Part 1: Fundamentals of Projected-Capacitive Touch Technology

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Must use exact capitalization!

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Agenda

- Introduction
- Basic Principles
- Controllers
- Sensors
- ITO-Replacement Materials
- Modules
- Embedded
- Large-Format
- Stylus
- Software
- Conclusions
- Appendix A: Historical Embedded Touch

Introduction

- P-Cap History
- P-Cap Penetration
- P-Cap by Application
- Touch User-Experience

Must use exact capitalization!

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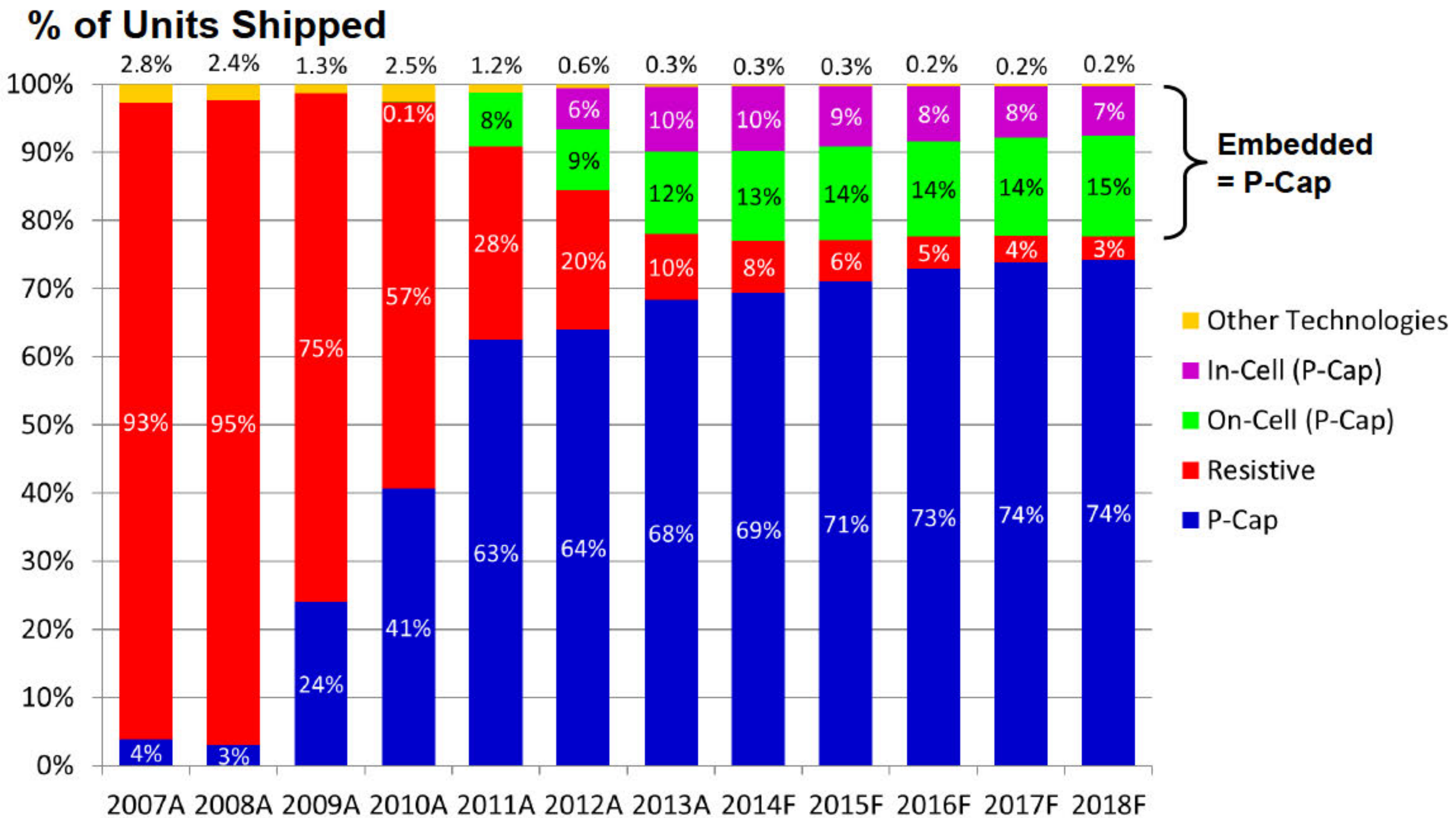
P-Cap History

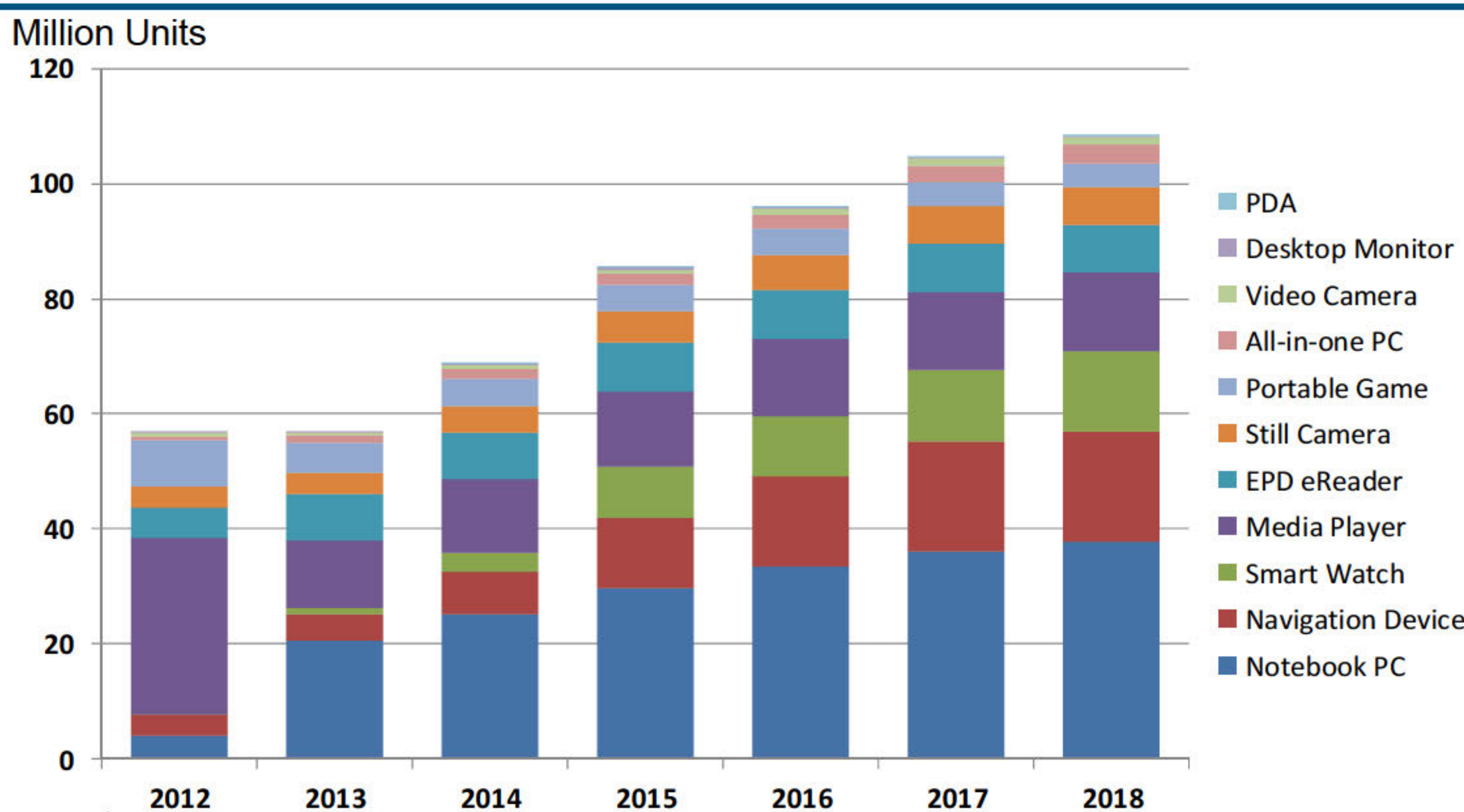
Company	Significance	Year
UK Royal Radar Establishment (E.A. Johnson)	First published application of transparent touchscreen (mutual-capacitance p-cap on CRT air-traffic control terminals)	1965
CERN (Bent Stumpe)	Second published application of mutual-capacitance p-cap (in the control room of the CERN proton synchrotron)	1977
Dynapro Thin Films (acquired by 3M Touch Systems in 2000)	First commercialization of mutual-capacitive p-cap (renamed as Near-Field Imaging by 3M)	1995
Zytronic (first license from Ronald Binstead, an inventor in the UK)	First commercialization of large-format self-capacitive p-cap; first commercialization of large-format mutual-capacitive p-cap	1998 2012
Visual Planet (second license from Ronald Binstead)	Second commercialization of large-format self-capacitive p-cap	2003
Apple	First use of mutual-capacitive p-cap in a consumer electronics product (the iPhone)	2007

P-Cap Penetration



Source: DisplaySearch Touch-Panel Market Analysis Reports 2008-2014

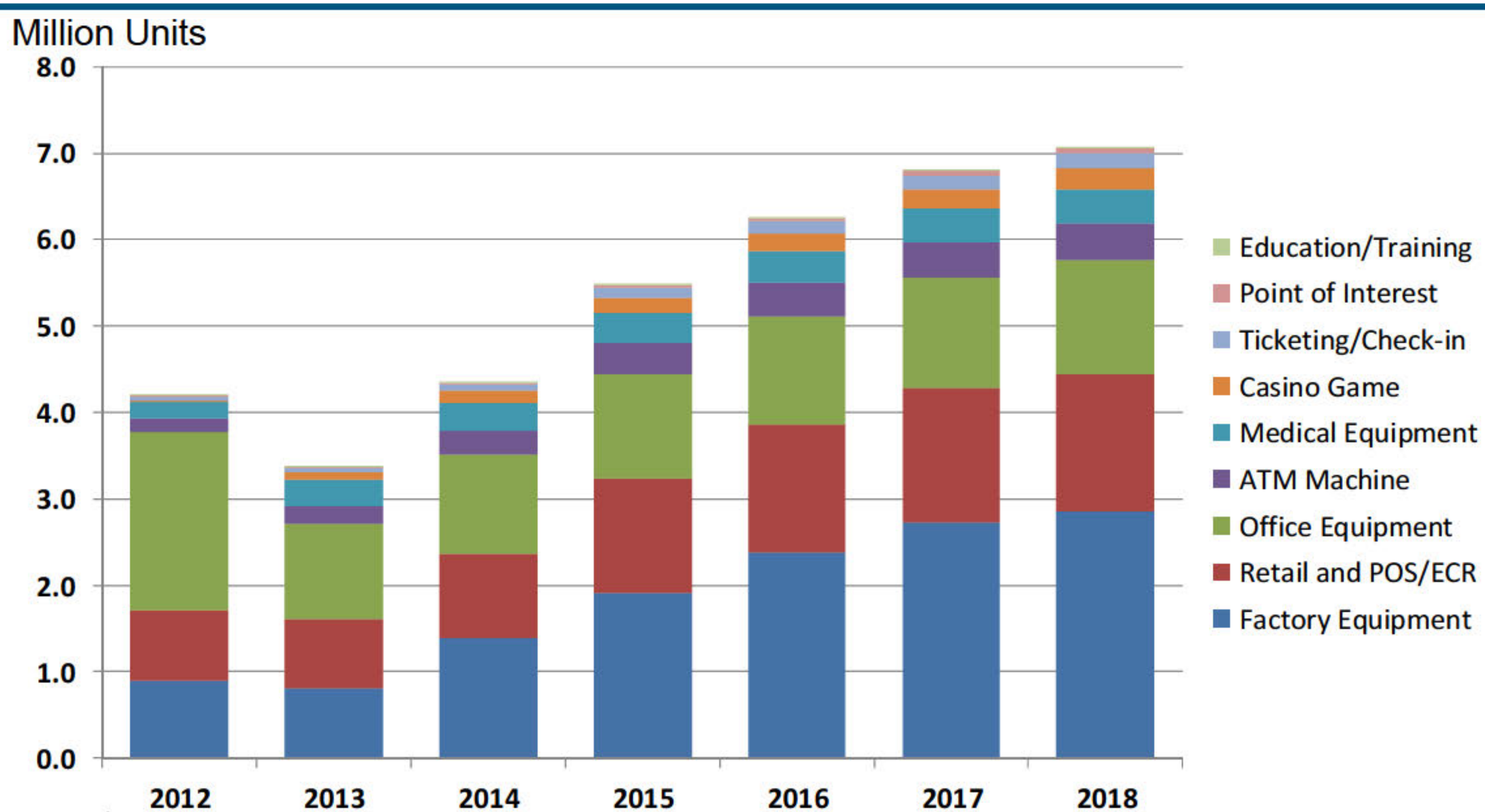
P-Cap Forecast by Application…1 (Consumer)



2018: Phones = **1.8 Billion** Units; Tablets = **447 Million** Units

Source: DisplaySearch Touch-Panel Market Analysis Report 1Q-2014

P-Cap Forecast by Application…2 (Commercial)



2018: Automobile Monitor = **42 Million** Units

Source: DisplaySearch Touch-Panel Market Analysis Report 1Q-2014

P-Cap Defines the Standard for Touch User-Experience

- **Smartphones and tablets have set the standard for touch in *SEVERAL BILLION* consumers' minds**
  - Multiple simultaneous touches (robust multi-touch)
  - Extremely light touch (zero force)
  - Flush surface ("zero-bezel" or "edge-to-edge")
  - Excellent optical performance
  - Very smooth & fast scrolling
  - Reliable and durable
  - An integral part of the device user experience

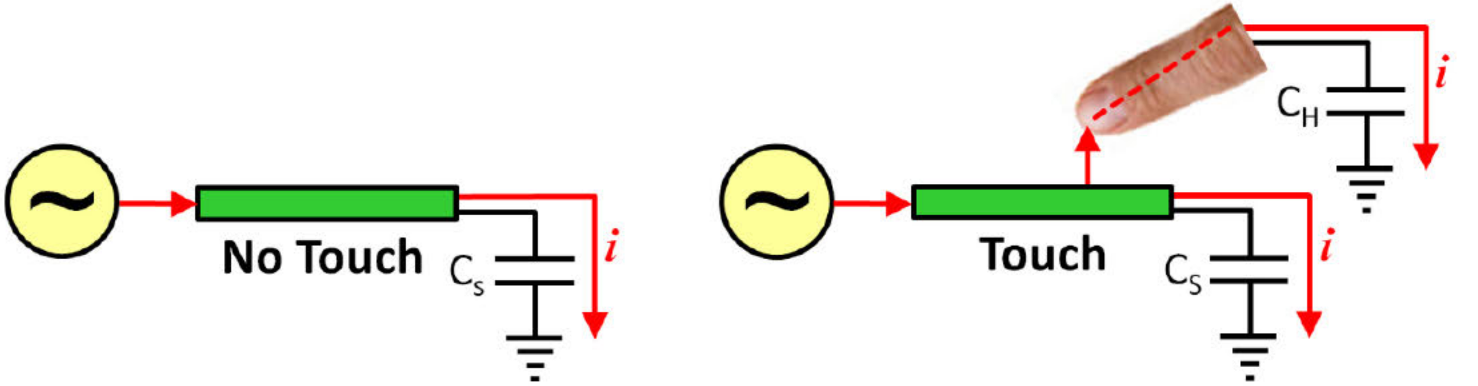
Source: AP / NBC News

Basic Principles

- Self Capacitive
- Mutual Capacitive
- Mutual Capacitive Electrode Patterns

Self-Capacitance

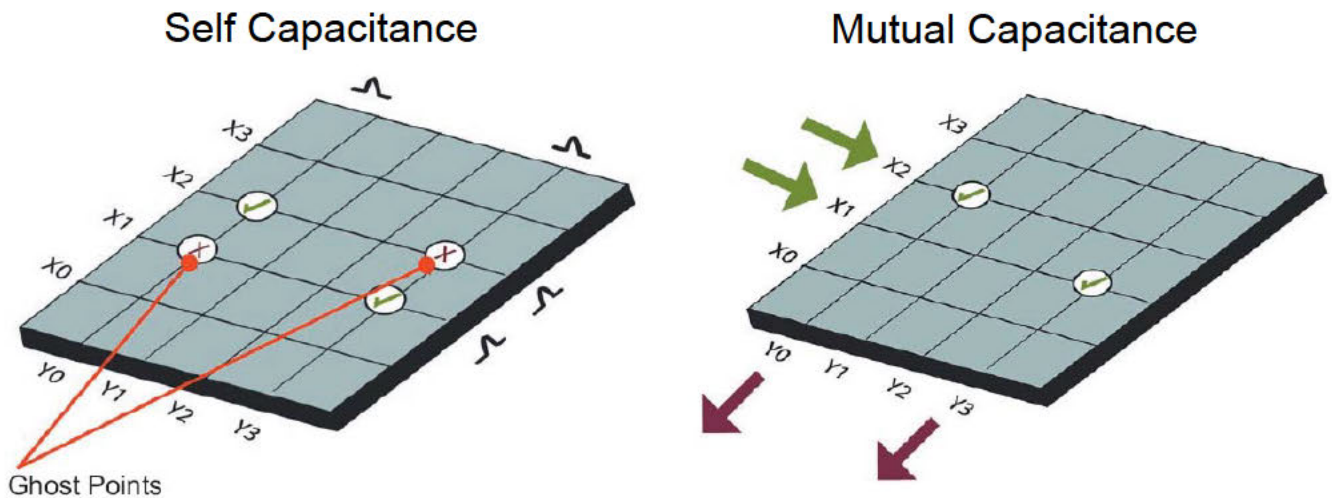
- **Capacitance of a single electrode to ground**
  - Human body capacitance increases the capacitance of the electrode to ground
  - In a self-capacitance sensor, each electrode is measured individually



Source: The author

The Problem with Self-Capacitance

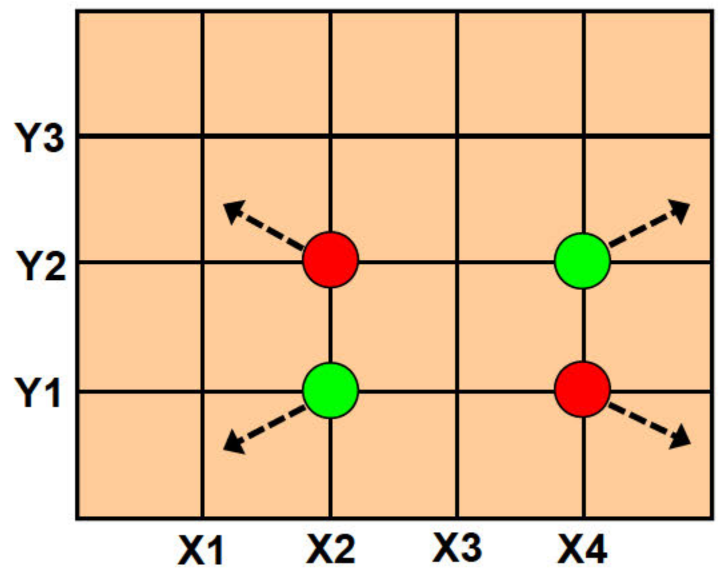
- **Touches that are diagonally separated produce <u>two maximums on each axis</u> (real points & ghost points)**
  - Ghost points = False touches positionally related to real touches



Source: Atmel

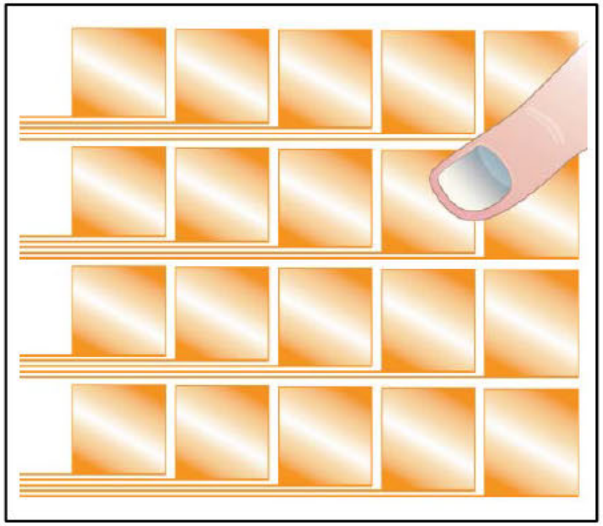
Self-Capacitance and Pinch/Zoom Gestures

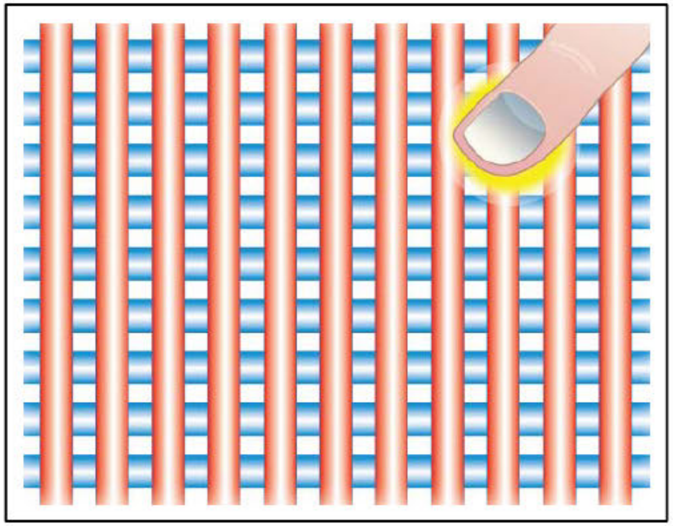
- Use the direction of movement of the points rather than the ambiguous locations



Source: The author

Self-Capacitance Electrode Variations





20 measurements

Source: 3M

20 measurements

- Multiple separate pads in a single layer
- Each pad is scanned individually

- Rows and columns of electrodes in two layers
- Row & column electrodes are scanned in sequence

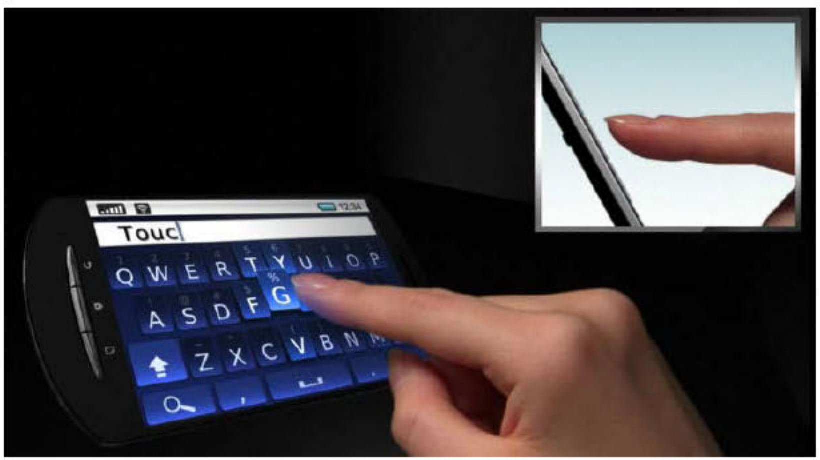
Self-Capacitance Advantages & Disadvantages

Self-Capacitive Advantages	Self-Capacitive Disadvantages
Simpler, lower-cost sensor	Limited to 1 or 2 touches with ghosting
Can be a single layer	Lower immunity to LCD noise
Long-distance field projection	Lower touch accuracy
Can be used with active guard	Harder to maximize SNR
Fast measurement	

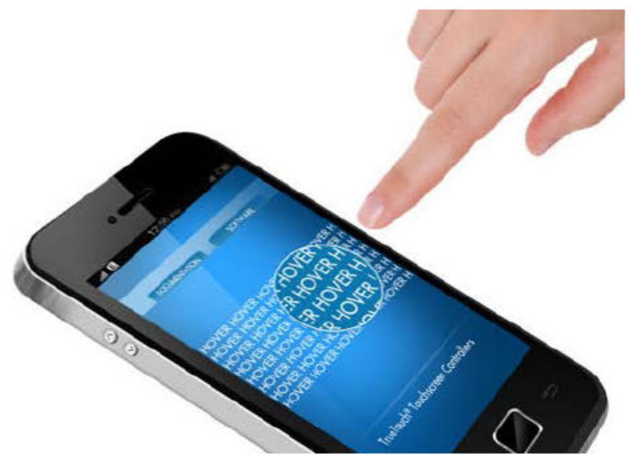
- **Where it's used**
  - Lower-end smartphones and feature-phones with touch
    - Becoming much less common due to single-layer p-cap
  - In combination with mutual capacitance to increase capability

Self-Capacitance for Hover

- **Self-capacitance is used to produce "hover" behavior in some smartphones (in addition to mutual-capacitance for contact-touch location)**
  - Also used for automatically detecting glove vs. fingernail vs. skin, and for dealing with water on the screen



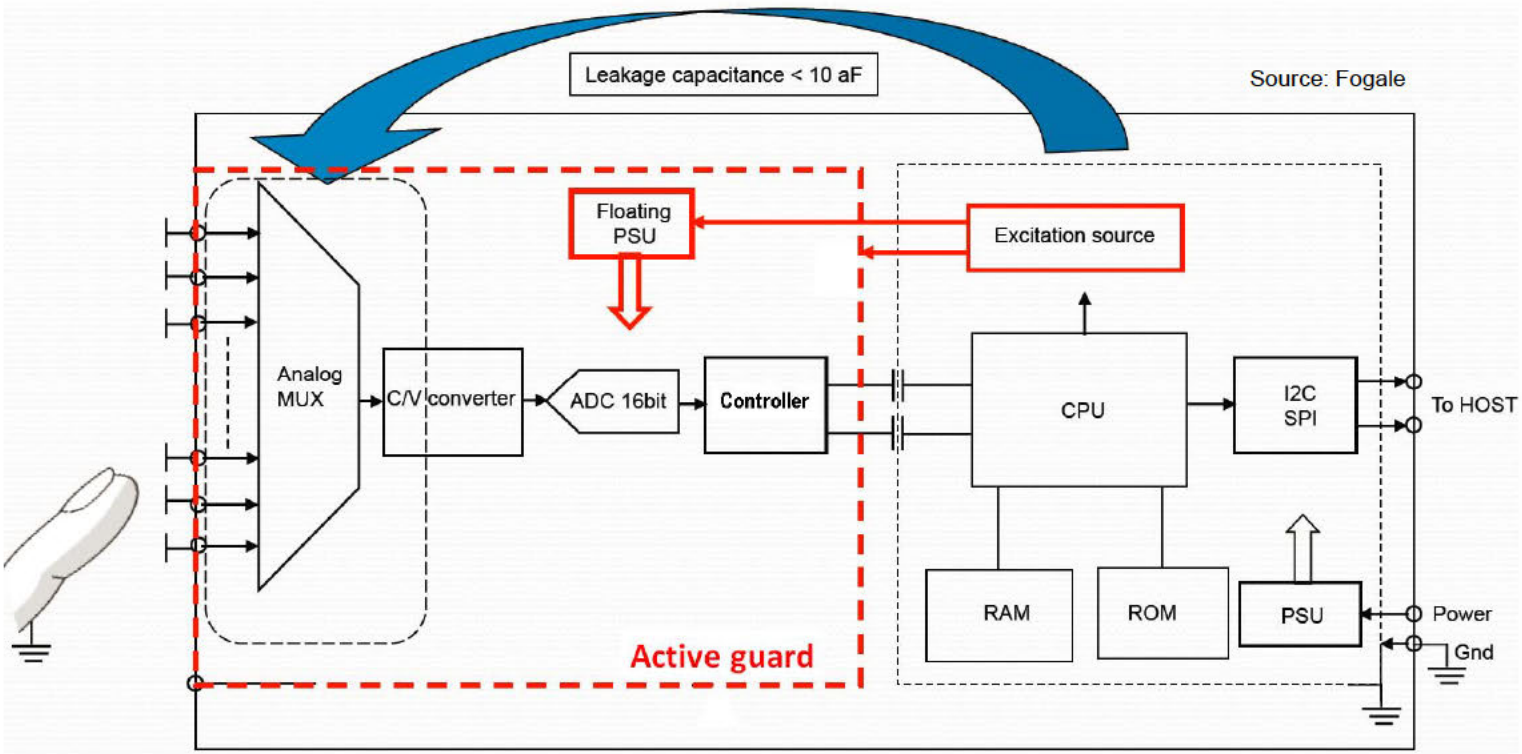
Source: Panasonic



Source: Cypress

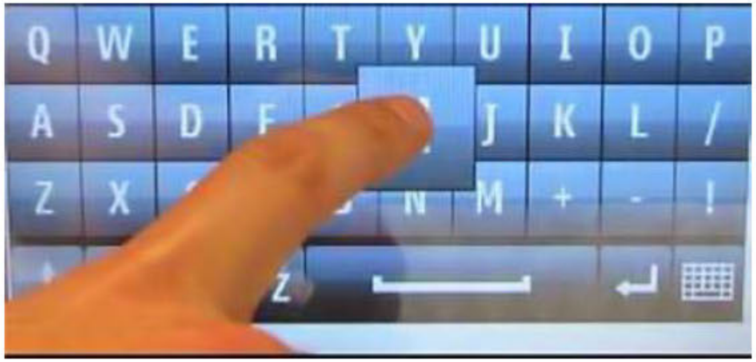
Multi-Touch Self-Capacitance Using Active Guard Concept…1

❖ **Guarding is a well-known technique for reducing the effects of electrical current leakage**



Multi-Touch Self-Capacitance Using Active Guard Concept…2

- Another contender: zRRo



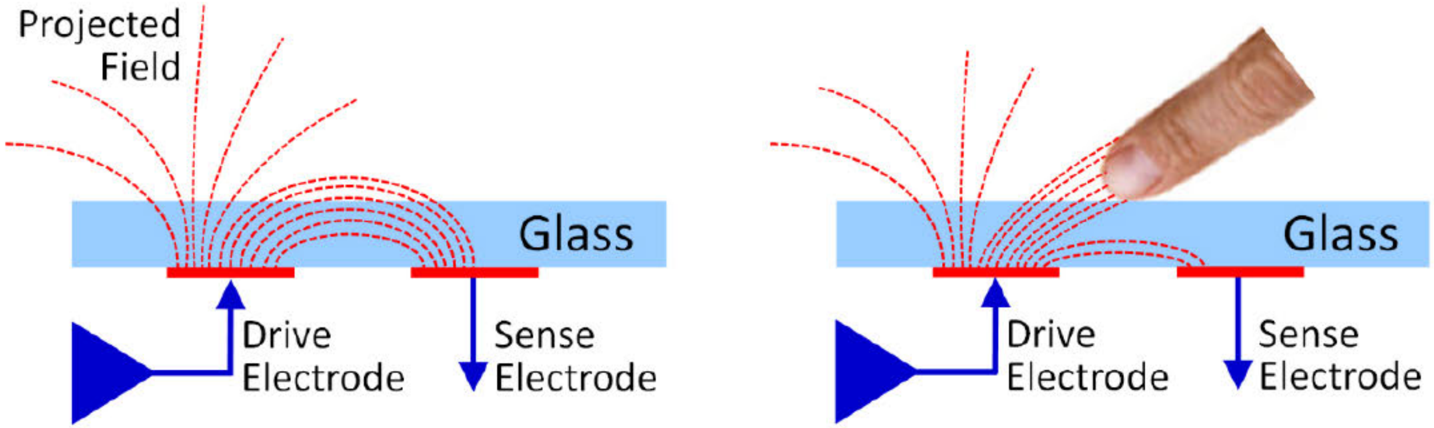
3D single-touch for smartphones

3D multi-touch for smartphones and tablets

Source: zRRo

Mutual Capacitance

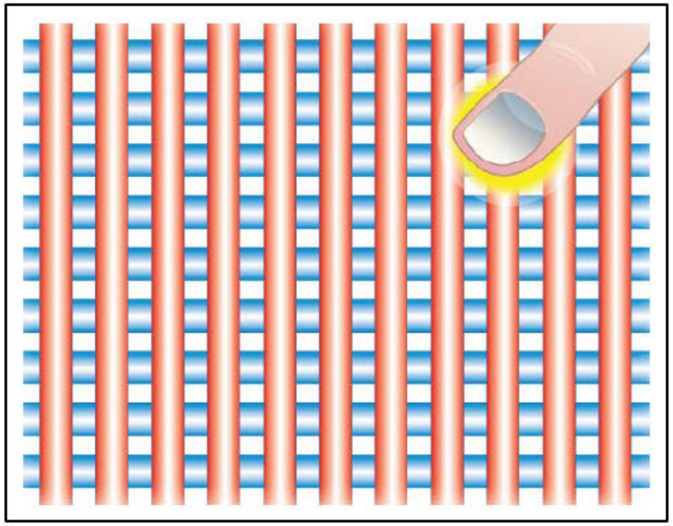
- Capacitance **between two electrodes**
  - Human body capacitance "steals charge" which decreases the capacitance between the electrodes
  - In a mutual-capacitance sensor, each electrode intersection is measured individually



Source: The author

Mutual Capacitance Electrode Patterns…1

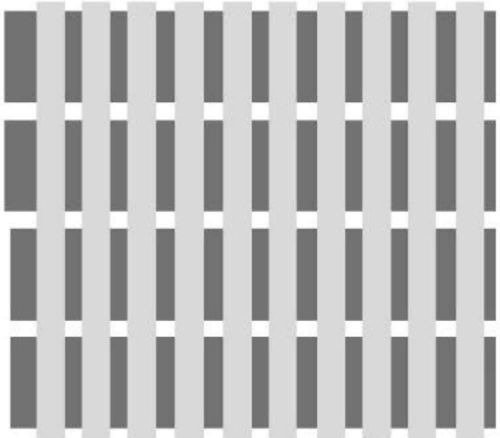
- Rows and columns of electrodes in two layers



Source: 3M

11 x 9 = 99 measurements

- In the real world…
  - "Bar and stripe", also called "Manhattan" or "Flooded-X" (LCD noise self-shielding)

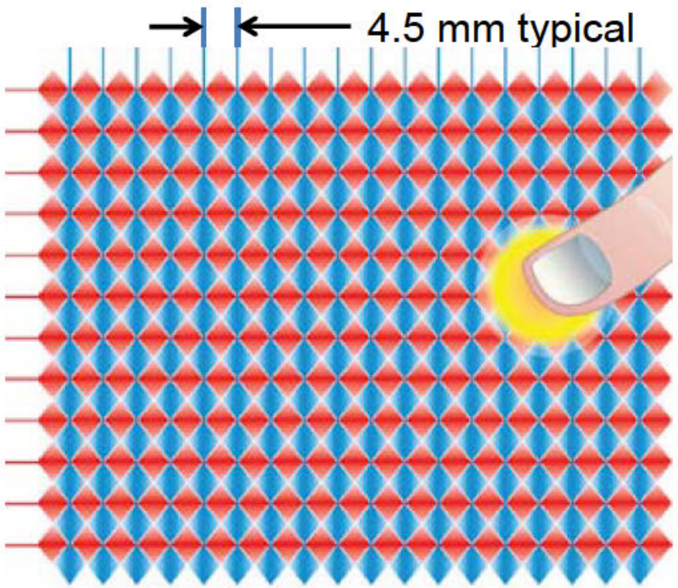


Source: Cypress

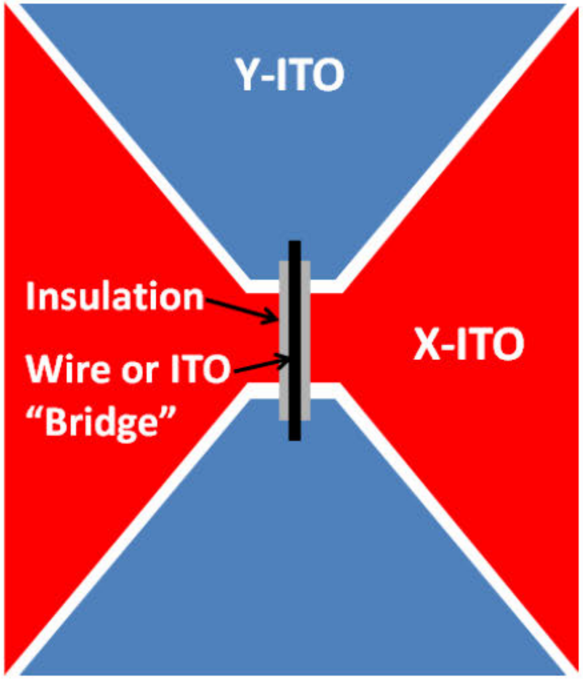
4 x 10 = 40 measurements

Mutual Capacitance Electrode Patterns…2

❖ **Interlocking diamond pattern with ITO in "one layer" with *bridges***



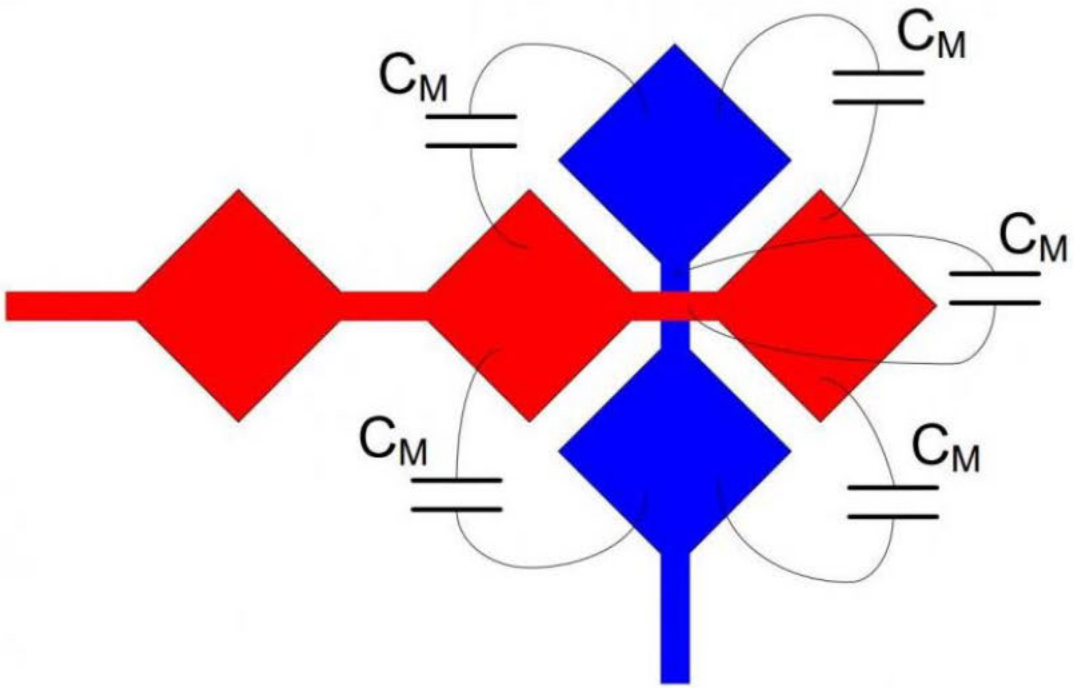
Source: 3M



Source: The author

More On Mutual Capacitance…1

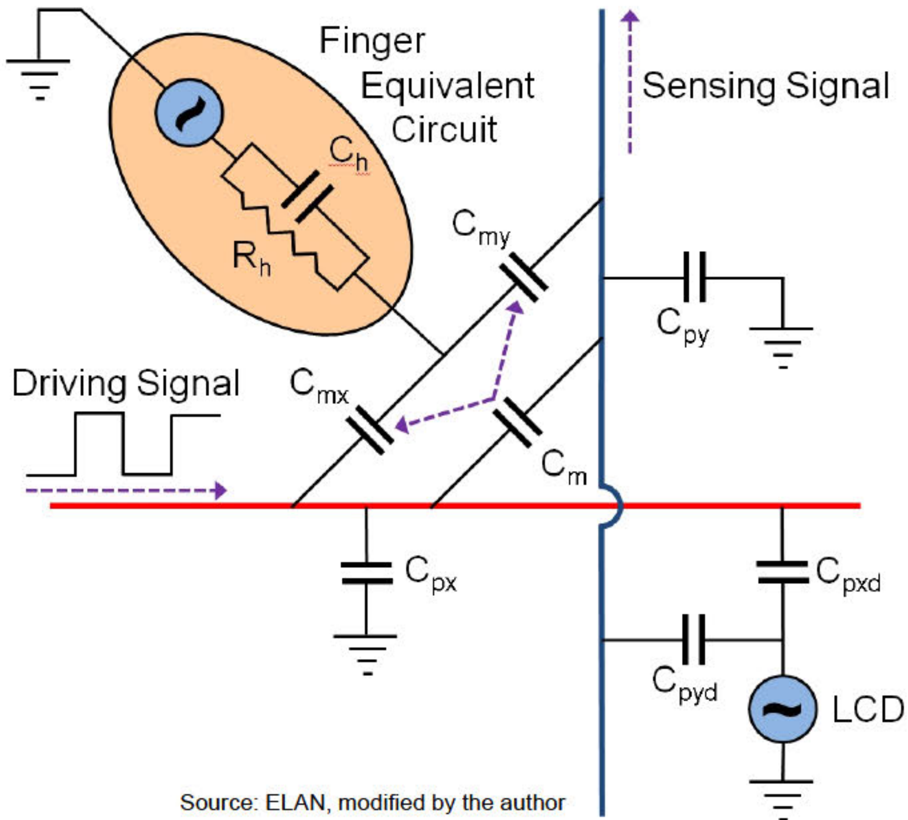
❖ **BTW, there isn't just <u>one</u> mutual capacitance…**



Source: Cypress

More On Mutual Capacitance…2

❖ And there are more capacitors than just the C_m's…



Source: ELAN, modified by the author

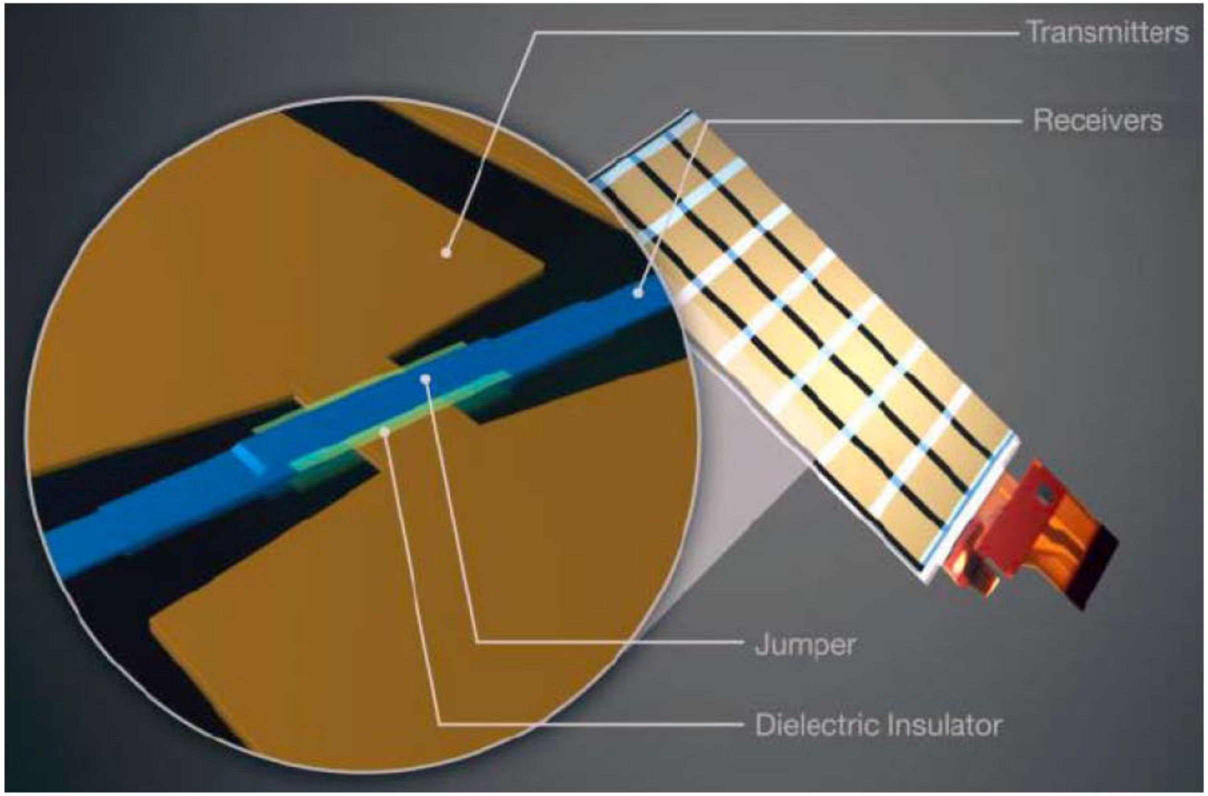
More On Mutual Capacitance…3

Mutual-Capacitive Advantages	Mutual-Capacitive Disadvantages
2 or more unambiguous touches	More complex, higher-cost controller
Higher immunity to LCD noise	2 layers (or 1 with bridges) for >3 pts
Higher touch accuracy	
More flexibility in pattern design	
Easier to maximize SNR	

- **Where it's used**
  - Mid & high-end smartphones, tablets, Ultrabooks, AiOs, commercial products
    - Standalone self-capacitive is becoming increasingly rare in consumer electronics (except for buttons)
  - With "true single-layer" sensors in low-end smartphones

Mutual Capacitance Electrode Patterns…3

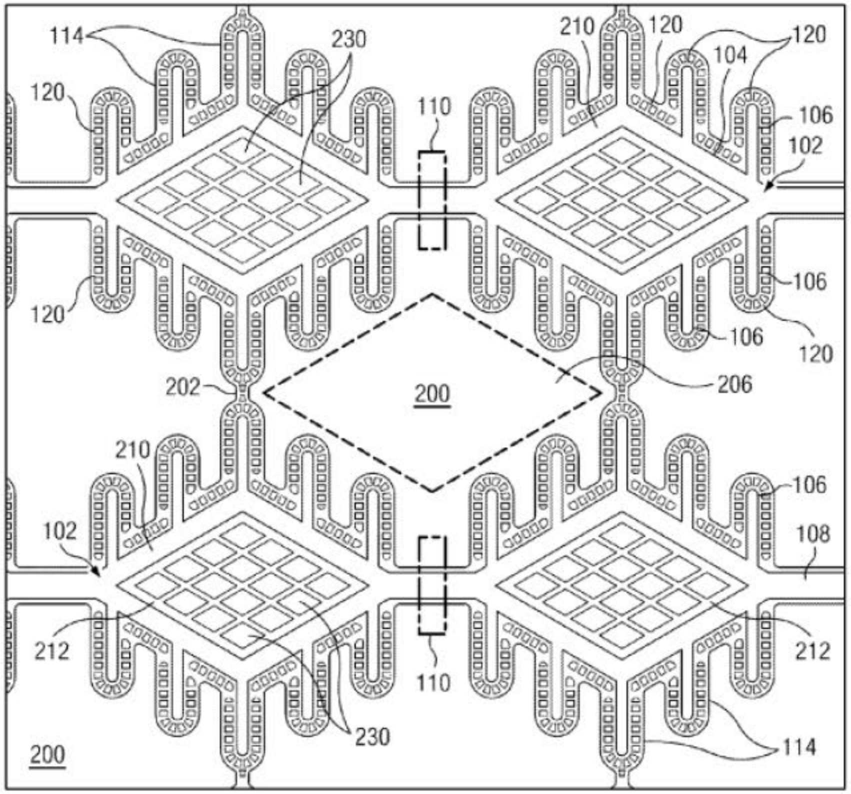
- Bars & stripes require bridges too…



Source: Synaptics

Mutual Capacitance Electrode Patterns…4

❖ **And so does this unusual diamond pattern…**



Source: STMicro

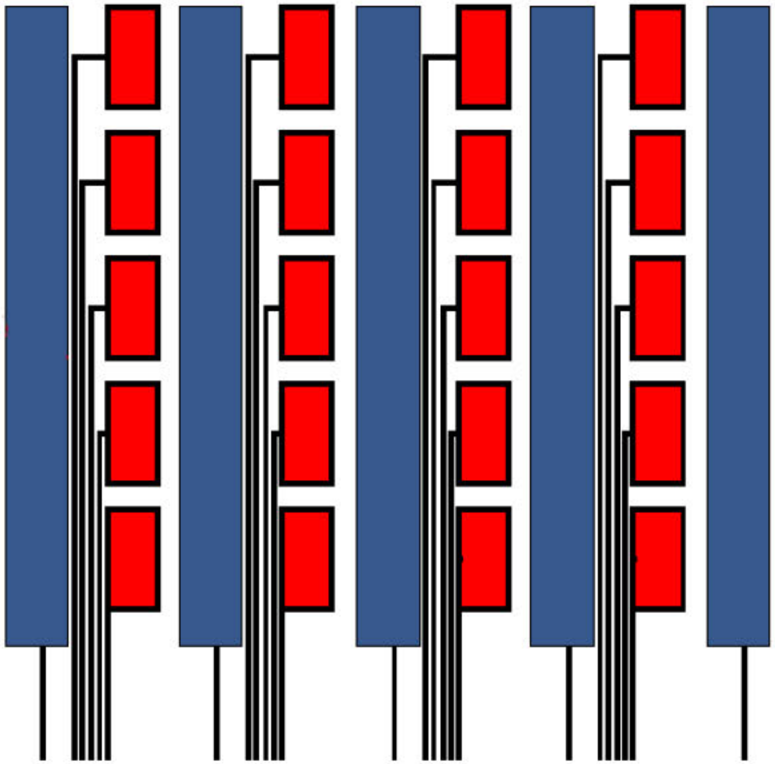
- 102, 106, 108, 210
  - Drive (X) electrodes
- 114 & 202
  - Sense (Y) electrodes
- 110
  - Bridges
- 120 & 230
  - Dummy (floating) ITO
- 200 & 206
  - Optional dummy ITO
- 212
  - Blank (no ITO)

Mutual Capacitance Electrode Patterns…5

- **Claimed advantages of this particular pattern over traditional interlocking diamond**
  - Reduction in sense electrode area reduces LCD noise pickup
  - "Finger projections" (0.1 – 0.2 mm) increase the perimeter of interaction between drive and sense electrodes, which increases sensitivity
  - Linearity is improved due to more uniform coupling across channels
  - Floating separators aid in increasing the fringing fields, which increases sensitivity

Mutual Capacitance Electrode Patterns…6

❖ **Holy Grail: True single-layer mutual capacitance sensor**



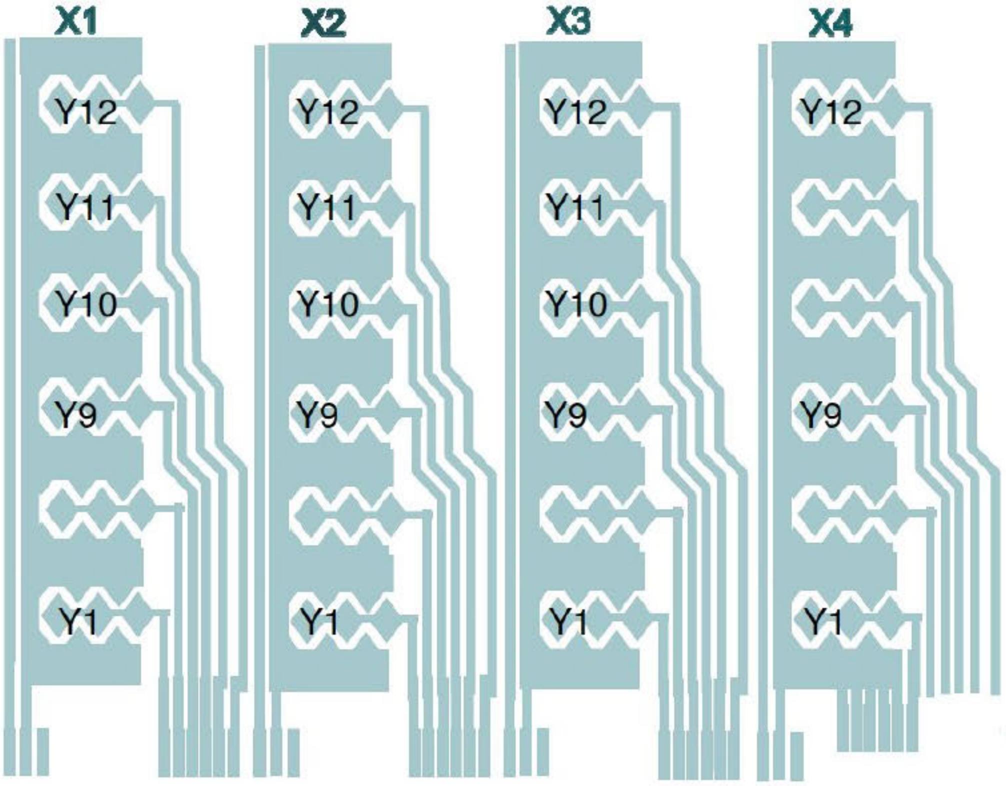
Source: Synaptics

❖ **"Caterpillar" pattern**

- ✦ Everybody's single-layer patterns are proprietary
- ✦ Requires fine patterning, low sheet resistance & low visibility
- ✦ Benefits: Narrow borders, thin stack-ups, lower cost, can reliably handle 2-3 touches

Mutual Capacitance Electrode Patterns…7

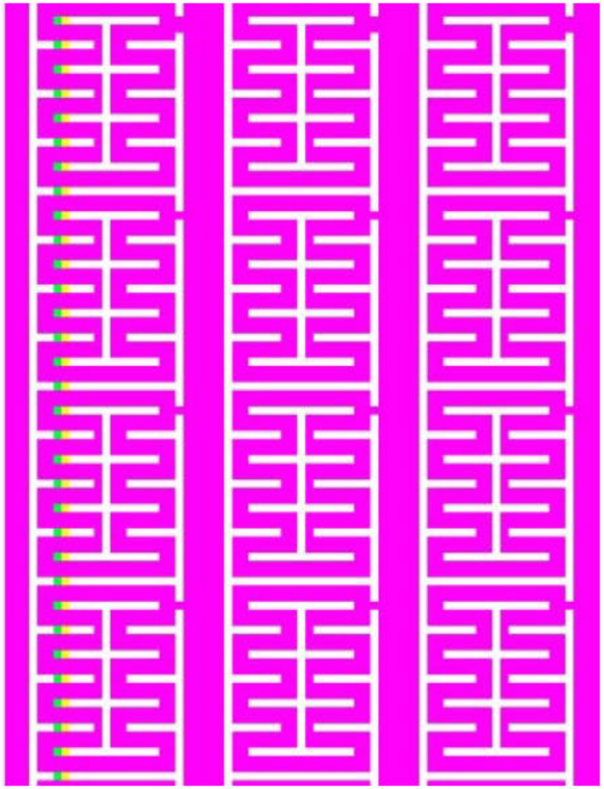
❖ **ELAN's caterpillar pattern**



Source: ELAN

Mutual Capacitance Electrode Patterns…8

- An alternative true single-layer pattern from ELAN
  - This is a very small portion of a much larger sensor

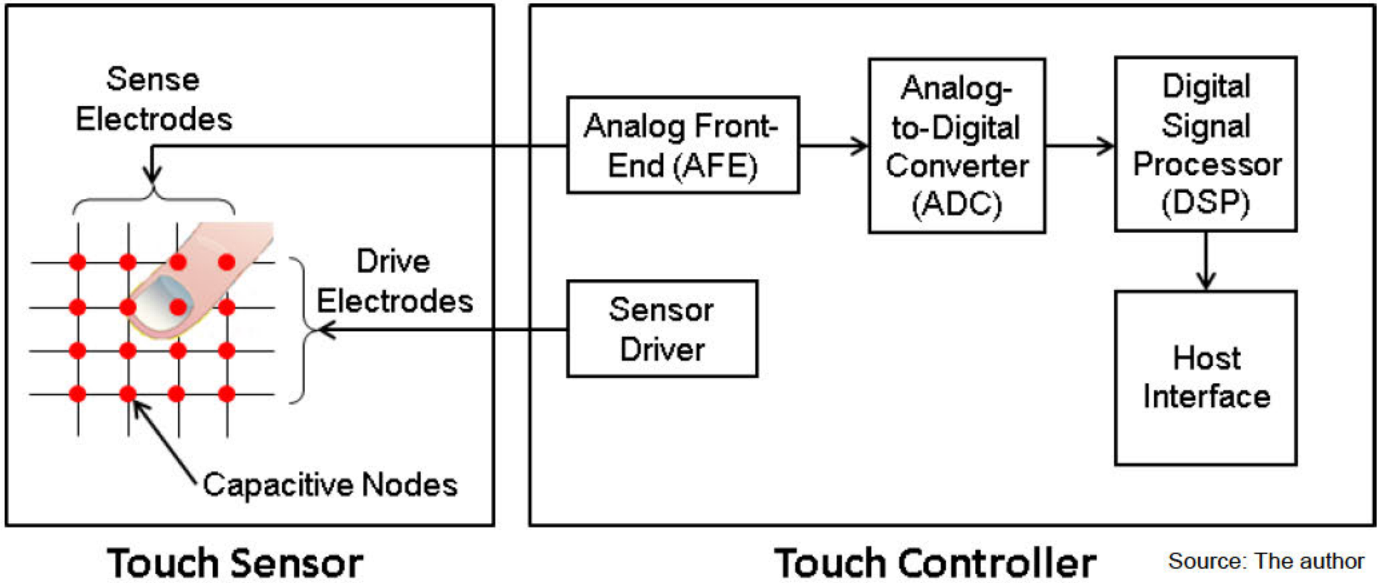


Source: ELAN

Controllers

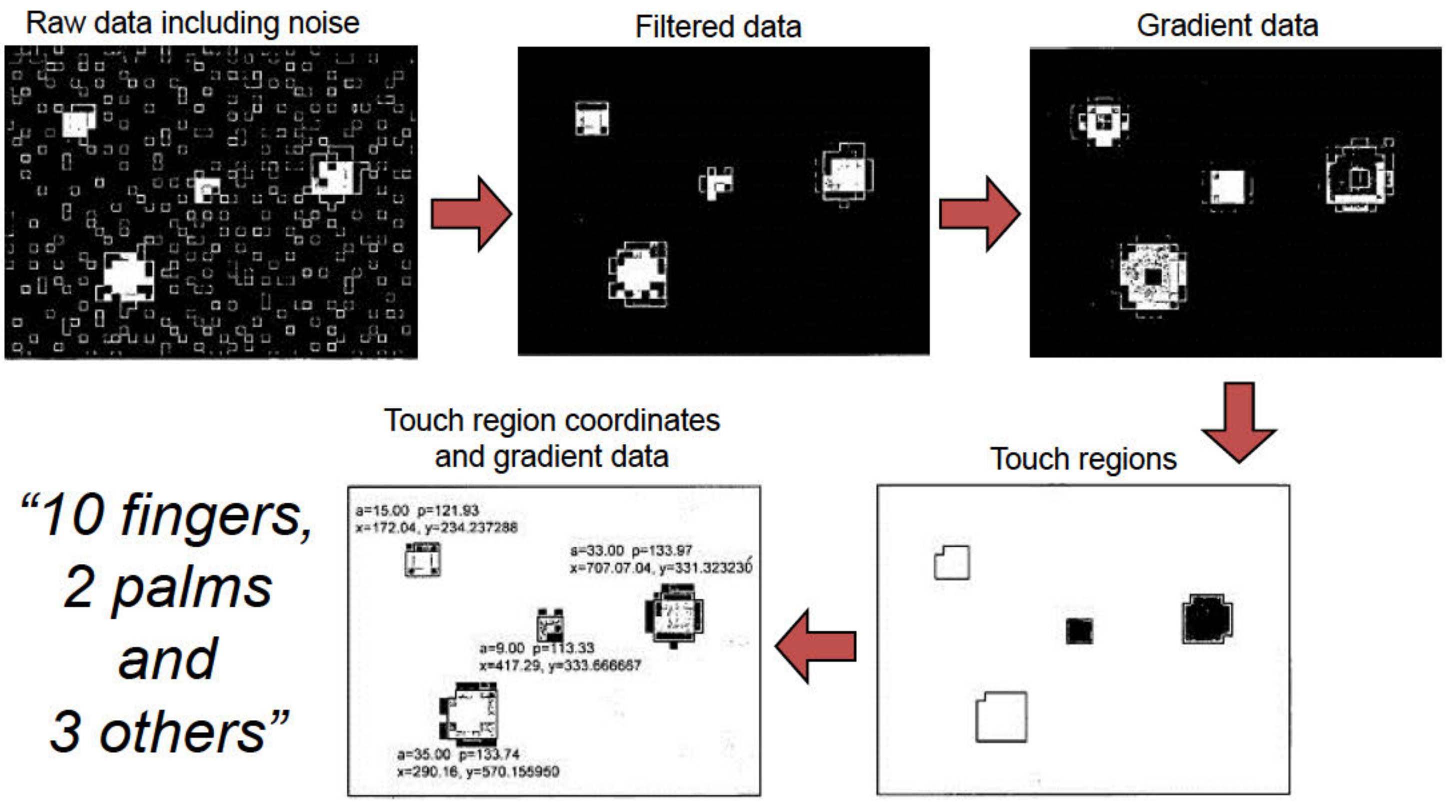
- Architecture
- Touch Image Processing
- Key Characteristics
- Signal-to-Noise Ratio
- Noise Management
- Innovation Areas
- Suppliers

Mutual Capacitance Touch System Architecture



- Making X*Y measurements is OK, but it's better to measure the columns simultaneously
- Controllers can be ganged (operate in a master-slave relationship) for larger screens

Touch Image Processing



"10 fingers, 2 palms and 3 others"

Source: Apple Patent Application #2006/0097991

Key Controller Characteristics…1

- **Node count (x channels + y channels)**
  - Given typical electrode spacing of 4.5 to 5 mm, this determines how large a touchscreen the controller can support (w/o ganging)
- **Scan rate**
  - Frames per second (fps) – faster reduces latency for a better UX
  - Windows logo requires 100 fps; Android is unspecified
- **Signal-to-noise ratio (SNR)**
  - More info on upcoming slides
- **Operating voltage & current**
  - OEMs continue to request lower-power touchscreen systems
  - Win8 "Connected Standby" is a significant influence
- **Internal core (micro/DSP)**
  - Varies from small 8-bit micro to ARM-7 or higher

Key Controller Characteristics…2

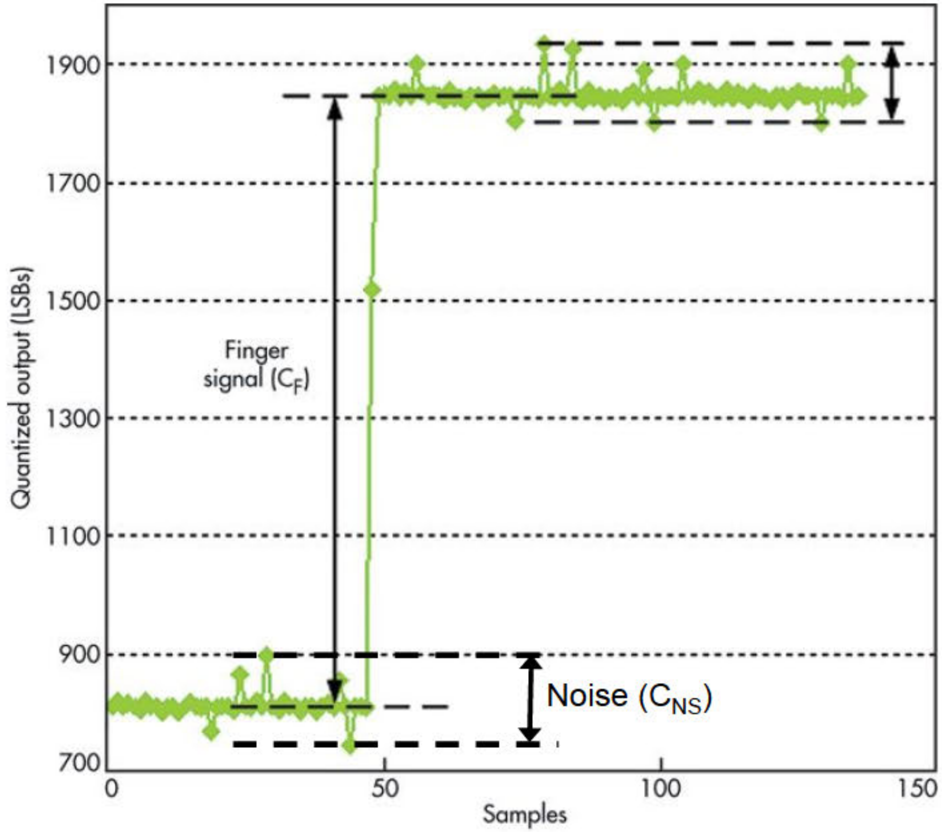
- **Number of simultaneous touches**
  - Windows Logo requires 5 (except AiO = 2); Android is unspecified
  - Market trend is 10 for tablets and notebooks
- **Support for unintended touches**
  - "Palm rejection", "grip suppression", etc.
  - Rarely specified, but critically important
  - For a 22" screen, even 50 touches isn't too many in this regard
- **Amount of "tuning" required**
  - Never specified – more info on upcoming slide

Signal-to-Noise Ratio (SNR)…1

- **SNR = Industry-standard performance metric for p-cap touchscreen systems**
  - However, no standard methodologies exist for measuring, calculating, and reporting SNR
  - The two components (signal & noise) depend heavily on the device under test
- **Noise from displays (LCDs & OLEDs) and from USB chargers is spiky – it doesn't have a normal (Gaussian) distribution – and spikes create jitter**
  - Yet marketers typically specify SNR <u>in the absence of noise</u>, using the <u>RMS noise</u> (standard deviation) of analog-to-digital convertors (ADCs)
  - With Gaussian noise, you can multiply the RMS noise by 6 to calculate the peak-to-peak noise with 99.7% confidence

Signal-to-Noise Ratio (SNR)…2

❖ Typical system (raw ADC data, no digital filters applied)



Source: Cypress
(modified by the author)

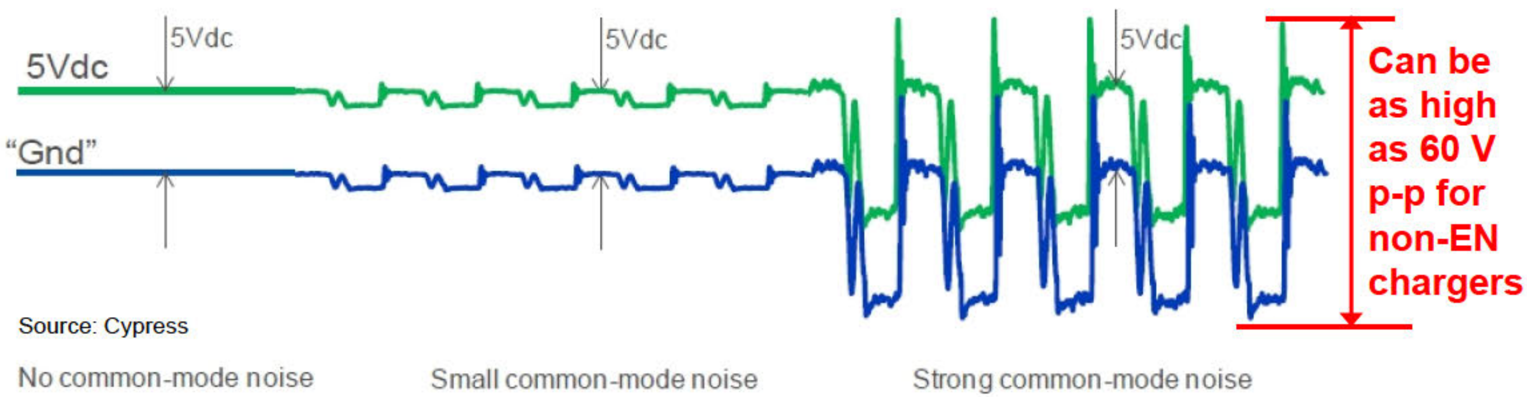
Signal-to-Noise Ratio (SNR)…3

- **SNR of system in previous slide**
  - C_{Finger} = Mean (Finger) - Mean (NoFinger)
  - C_{Finger} = 1850 - 813 = 1037
  - C_{NS} (Standard Deviation) = 20.6 counts
  - C_{NS} (Peak-to-Peak) = Max (NoFinger) - Min (NoFinger) +1
  - C_{NS} = 900 - 746 +1 = 155 counts
  - SNR (Peak-to-Peak) = 1037/155 = **6.7**
  - SNR (Standard Deviation) = 1037/20.6 = **49.9**
  - Highest SNR currently reported by marketer = 70 dB (**3,162***)

* Signal amplitude ratio in dB = $20\log_{10}(A_1 / A_0)$

Noise Management…1

- **Charger noise is common-mode**
  - A smartphone on a desk (not handheld) isn't grounded, so the entire phone moves relative to earth ground as it follows the noise
  - A touching finger provides an alternative path to ground, which is equivalent to injecting the noise at the finger location
  - The noise signal can be 10X to 100X that of the signal generated by the touching finger

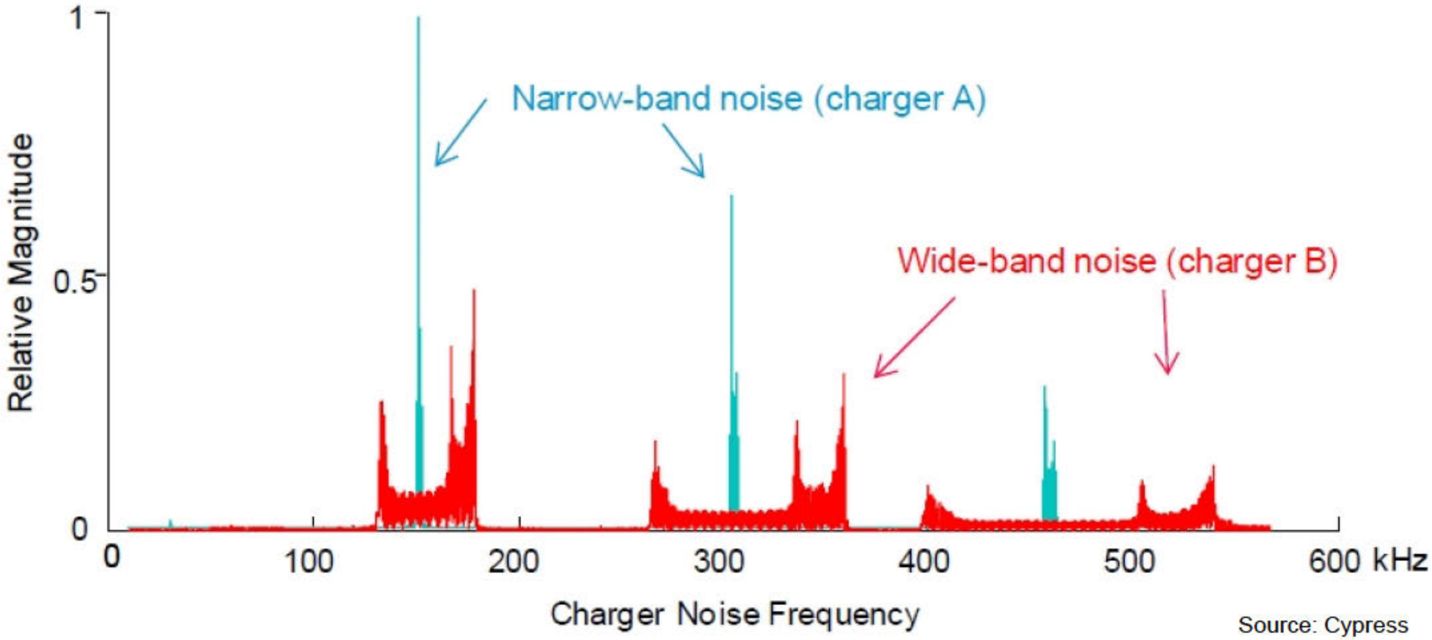


Source: Cypress

Noise Management…2

❖ **Examples of charger noise spectra**

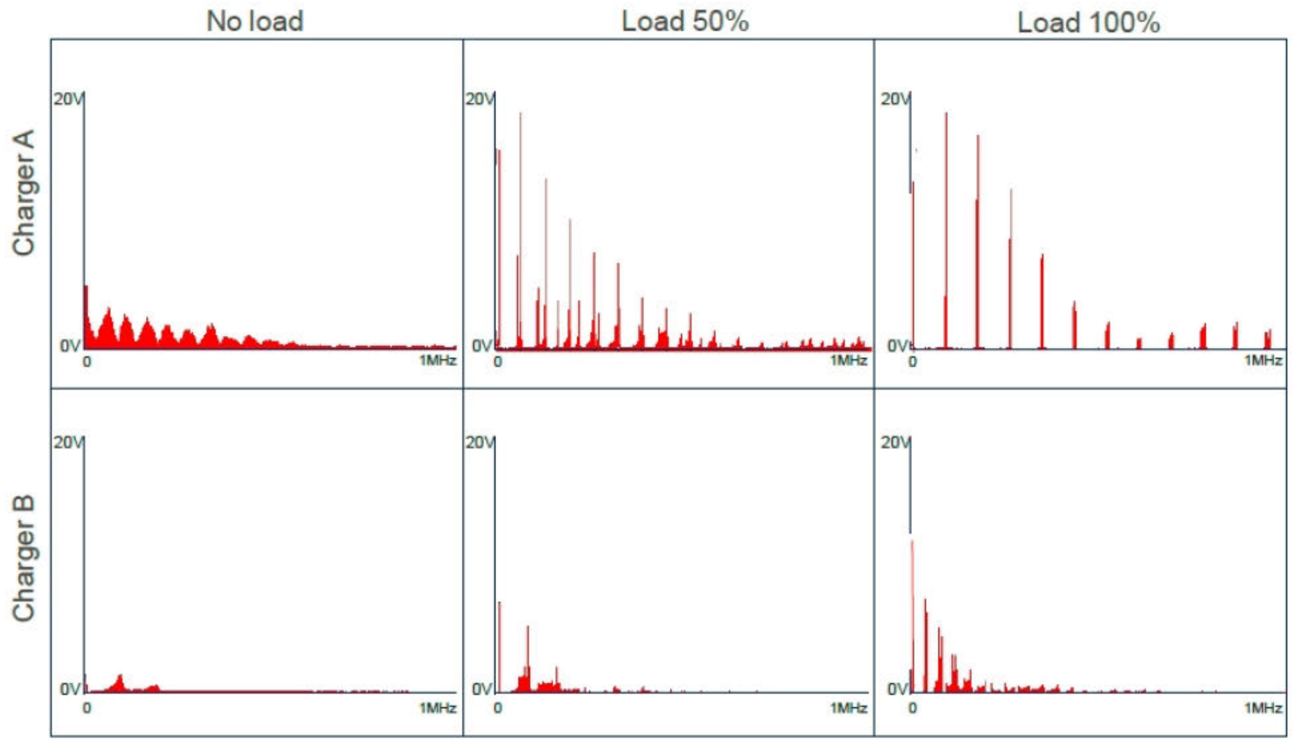
✦ Effect of noise is false or no touches, or excessive jitter



Source: Cypress

Noise Management…3

❖ **Variation in common-mode noise spectra in 2 different chargers at 3 different loads**



Source: Cypress

Noise Management…4

- **Techniques to combat charger noise**
  - Multiple linear and non-linear filters
  - Adaptive selection of the best operating frequency (hopping)
  - Increased drive-electrode voltage
    - Going from 2.7 V to 10 V increases SNR by 4X
  - Many proprietary methods
- **Display noise**
  - LCD noise is similar across the display; the high correlation of noise signals across all sensor signals allows relatively easy removal
  - Very high noise in embedded touch can require synchronization of the touch controller with the LCD driver (TCON)

Controller Innovation Areas

- **More information in upcoming slides**
  - Finger-hover
  - Glove-touch
  - Pressure sensing
  - Other touch-objects
  - Faster response (reduced latency)
  - Adaptive behavior
  - Water resistance
  - Software integration
  - Automated tuning
- **More information later in this course**
  - Passive and active stylus support

Finger-Hover…1

- **There are two ways of emulating "mouseover" on a p-cap touchscreen**
  - Hover over something to see it change, then touch to select
  - Press lightly on something to see it change, then press harder to select
- **The industry is moving towards hover because nobody has been able to implement pressure-sensing in a way that works well and that OEMs are willing to implement**
  - Startup: **NextInput**
    - Force-sensing using an array of organic transistors where pressure changes the gate current
  - Startup: **zRRo**
    - Multi-finger hover detection

Finger-Hover…2

- **What can you do with hover?**
  - Enlarge small links when you hover over them
  - Make a passive stylus seem to hover like an active stylus
  - Magnify an onscreen-keyboard key as you approach rather than after you've touched it, or even use a "Swipe" keyboard without touching it
  - Preview interactive objects such as an array of thumbnails
  - Use as an alternative to standard proximity detection
  - Use multi-finger gestures for more complex operations
  - And more…

Glove-Touch

- **Can be accomplished by adding self-capacitive to existing mutual-capacitive**
  - Mutual-capacitive provides touch location
  - Self-capacitive provides proximity sensing
  - Glove-touch causes the finger to remain a constant distance above the screen; proximity sensing can detect that without the user manually switching modes

Source: ELAN

Pressure Sensing

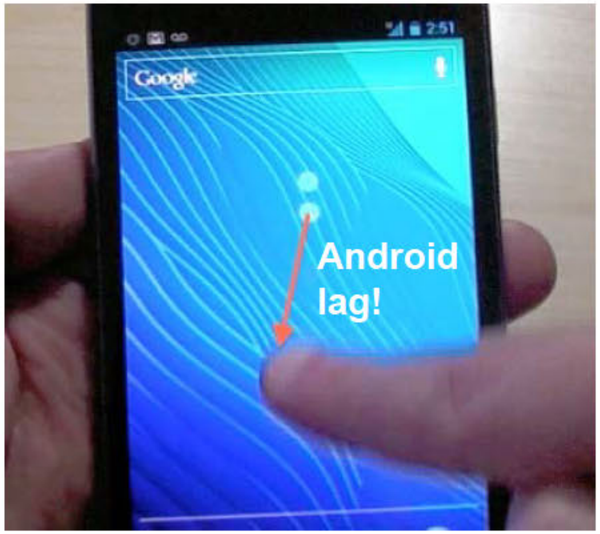
- **Pressure-sensing is an alternative selection method**
  - True absolute pressure-sensing in p-cap doesn't exist today
  - Some (including Microsoft) believe that "*touch lightly to view choices then press to select*" is more intuitive than hover
    - It has never been implemented successfully in a mobile device
      - Blackberry Storm (2 models!) failed due to terrible implementation
      - Nissha/Peratech (QTC) collaboration never made it into mass-production
  - Multiple startups are working on smartphone pressure-sensing
    - **NextInput**
      - Uses an array of pressure-sensitive organic transistors under the LCD
    - **FloatingTouch**
      - Mounts the LCD on pressure-sensing capacitors made using a 3M material

Other Touch Objects

- **You will soon be able to touch with a fine-tipped (2 mm) passive stylus, long fingernails, a ballpoint pen, a #2 pencil, and maybe other objects**
  - This is being accomplished through higher signal-to-noise (SNR) ratios
    - Much of this improvement may come from enhancing the controller analog front-end in addition to focusing on the digital algorithms
  - This enhancement to the UX will be the end of "finger-only" p-cap

Faster Response

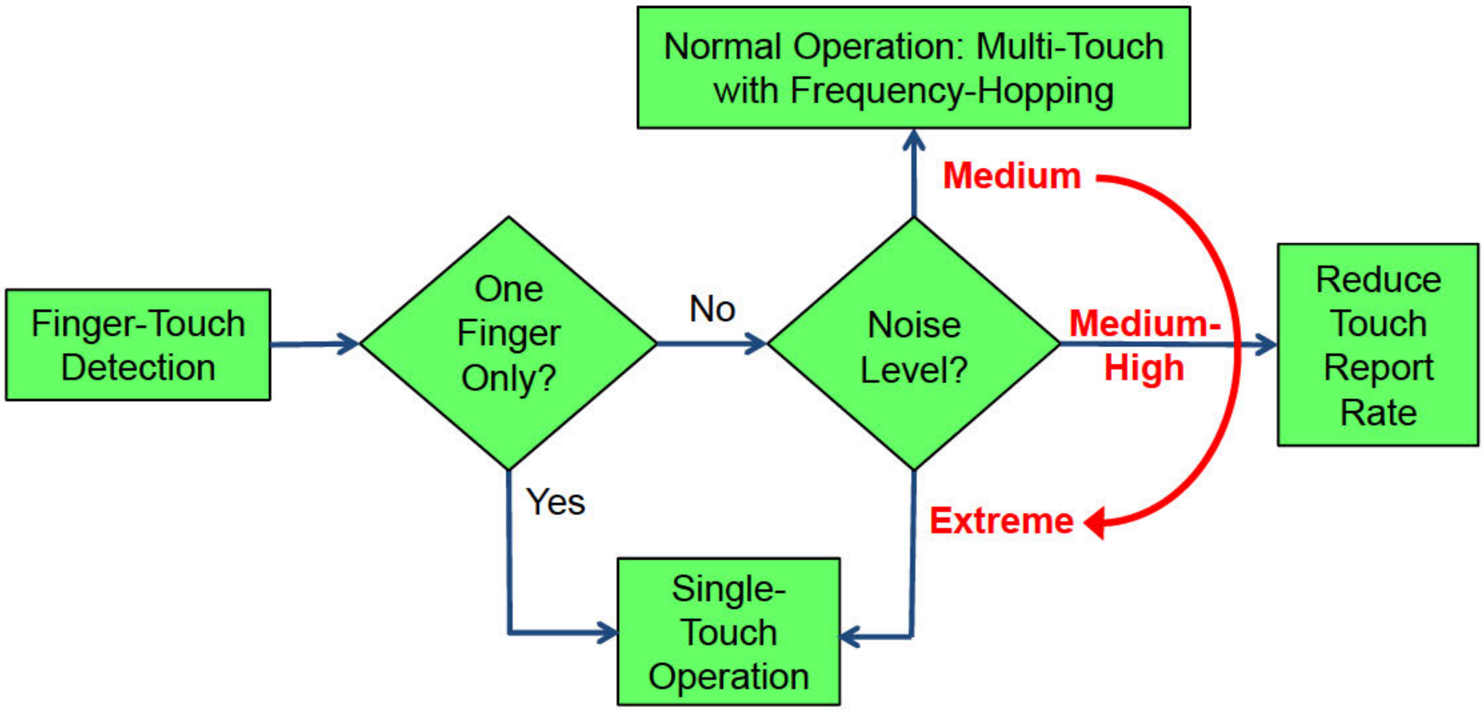
- **Make touch more natural by reducing latency**
  - The shorter the time is between a touch and the response, the better the user feels about the touch system
    - If an object lags behind your finger when you drag it, or ink lags behind a stylus when you're drawing, it doesn't feel real
  - Latency today is typically 75-100 ms; studies have shown that humans need less than 10 ms for comfort
    - Synaptics has addressed the problem by creating a direct path between the touch controller and the TCON to allow limited instant screen updates
    - **Tactual Labs** (startup) has a method of reducing latency to just a few milliseconds



Source: Gigaom.com

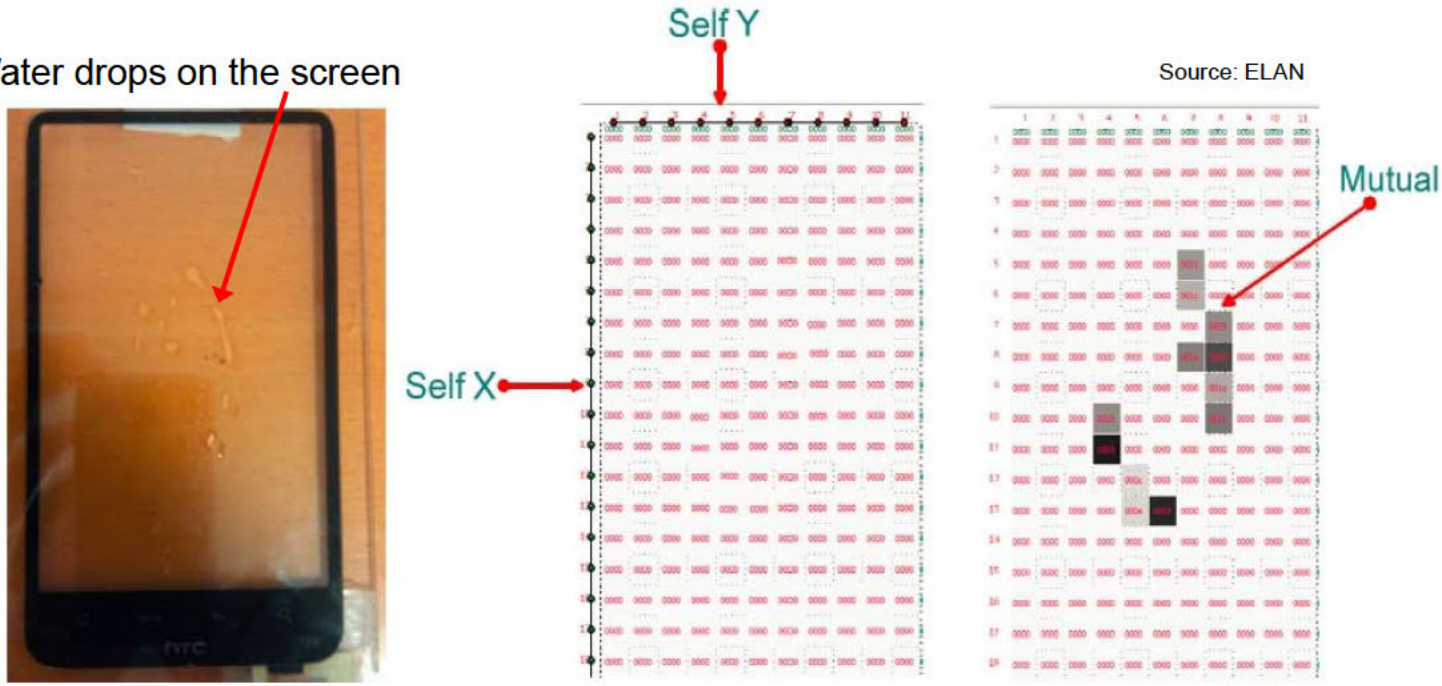
Adaptive Behavior: Noise Immunity

❖ **Adaptive noise-management by N-Trig**



Water Resistance…1

- The basic concept is combining self-capacitive and mutual-capacitive sensing (again)

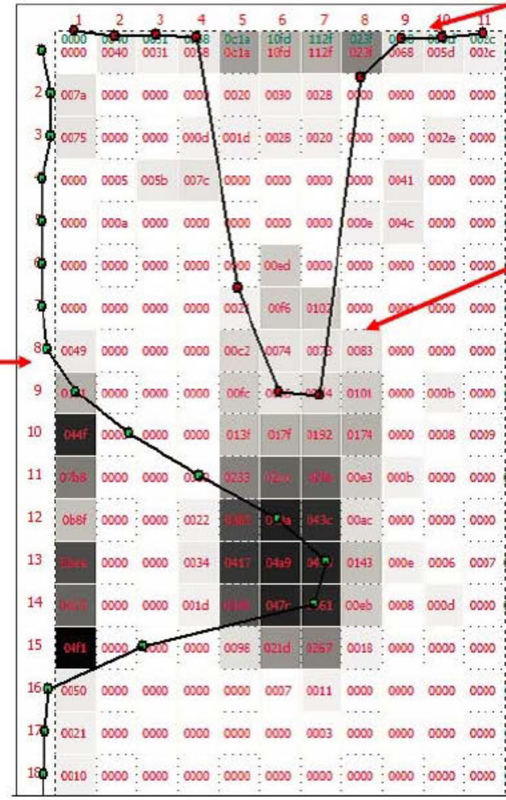


Water is not detected in self-capacitive mode

Water is detected in mutual-capacitive mode

Water Resistance…2

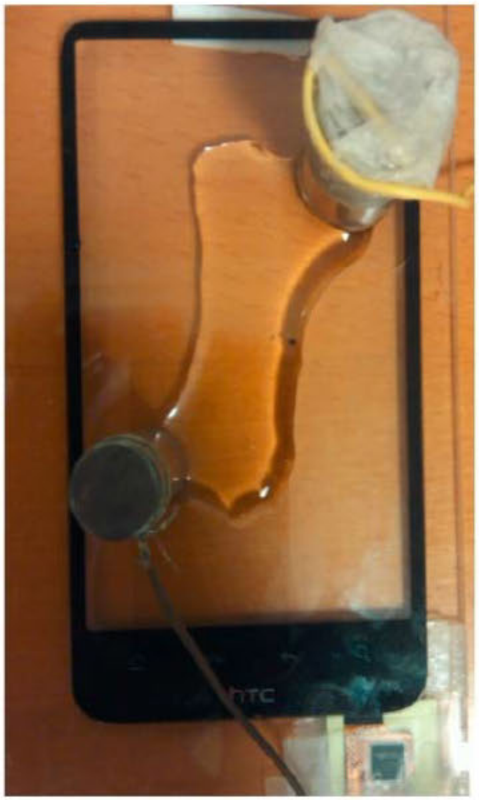
- A large amount of water with single-touch

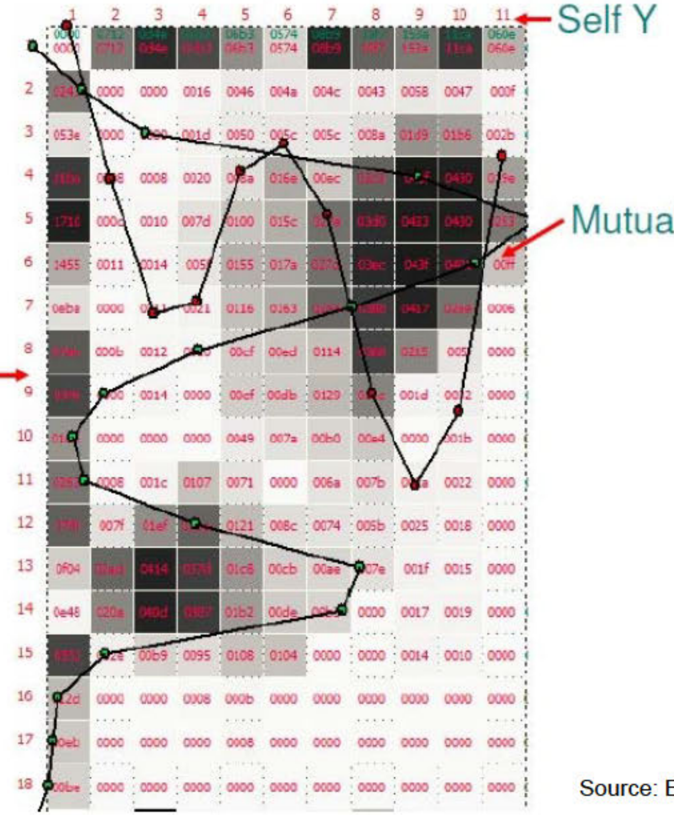


Source: ELAN

Water Resistance…3

❖ **A large amount of water with two touches**





Source: ELAN

Software Integration

- **Make more resources available to the touch controller**
  - Run touch algorithms on the GPU instead of the controller micro
    - Algorithm-writers can take advantage of much larger resources on the host device (MIPS and memory)
      - This can support higher frame-rate, reduced latency, reduced power consumption, easier support of different sensor designs, etc.
    - Algorithmic code is easier and faster to change when it's in a "driver" than when it's in firmware in an ASIC
      - Most touch-controller suppliers never change the firmware in the touch controller once it ships in a device; N-Trig is the sole exception
    - Cost-reduction by elimination of one micro
      - Even more cost reduction for large screens by elimination of slave chips
  - Something similar to this has already been done in NVIDIA's "Direct Touch", but it hasn't been widely used in actual devices

Automated Tuning

- **For true "touch everywhere", p-cap has to become like resistive: Just slap it on and you're done**
  - We're far from that point today
  - Atmel says that the typical first integration of a p-cap touch-panel into a new product takes one full day of tweaking up to 200 individual parameters
  - That badly needs to be automated so that small commercial product-makers have easier access to p-cap

P-Cap Controller Suppliers

- **In order by estimated 2013 revenue**

Company	Country
Broadcom (Apple)	USA
Atmel	USA
Synaptics	USA
TI	USA
FocalTech	China & Taiwan
Melfas	Korea
Cypress	USA
Goodix	China
ELAN	Taiwan
Mstar	Taiwan
EETI	Taiwan
Zinitix	Korea
SiS	Taiwan
Ilitek	Taiwan
Imagis	Korea
Sentelic	Taiwan
Weida	Taiwan
Sitronix	Taiwan

Top 7 (30%) account for about 85% of total revenue

And a few others…

- AMT
- Avago
- Pixcir
- Silicon Labs
- STMicro
- Weltrend

Sensors

- Substrates
- Structures
- Sheet vs. Piece Method
- More on OGS
- Glass Strengthening
- Surface Treatments
- ITO Index Matching
- Suppliers

Sensor Substrates…1

- **ITO film substrates are usually PET[1] or COP[2]**
  - Thickness has dropped from 100 μm to 50 μm
  - Lowest practical ITO sheet resistivity is currently ~100 Ω/□

- **ITO glass substrates**
  - Standard thickness for GG is 0.33 mm and 0.4 mm
  - Some makers have developed a thinning process (like for LCDs) that reduces glass thickness to 0.2 mm
  - Corning and AGC have developed 0.1 mm glass but it hasn't been used in volume sensor production yet
  - Lowest practical ITO sheet resistivity on glass is ~50 Ω/□

1 = Polyethylene Terephthalate
2 = Cyclic Olefin Polymer

Sensor Substrates…2

- PET film versus glass

	PET	Glass
Glass Transition Temperature	70°C	570°C
Aging Effects	Yellowing, curling, surface deformation	No known effect
Transparency	85%	=>90%
Resolution Capability	10-30 μm	1 μm
Stackup	Thinner	Thicker
Weight	Lighter	Heavier
Moisture Resistance	Good	Excellent
Lamination Yield	Excellent	Good
Mechanical Strengthening	None	Chemical, heat, ion-exchange
Cost	$$ (was < glass)	$

Sensor Structures…1

- Sensor structure abbreviations (for reference)

Symbol	Meaning
(G)	Cover-glass (or plastic or sapphire)
G	Cover-glass, or sensor-glass with ITO on one side, or plain glass for film lamination
GG	Cover-glass + one sensor-glass (without ITO location)
GGG	Cover-glass + two sheets of sensor-glass (rare)
G#	# = Number of ITO layers on one side of sensor-glass (G2 = "One Glass Solution" = OGS = SOC = SOL, etc.)
G1F	F = Sensor-film with ITO on one side, laminated to glass
GFF	FF = Two sensor-films, laminated to glass
GF#	1 = Two ITO layers on one side of sensor-film, laminated to glass (also called GF-Single) 2 = One ITO layer on each side of sensor-film, laminated to glass (also called GFxy with metal mesh)
SITO	ITO on one side of substrate (single-sided); usually includes metal bridges for Y to cross X
DITO	ITO on both sides of substrate (double-sided)
F1T	F1 = Single-sided sensor-film on top of CF glass; T = Transmit (drive) electrodes on TFT glass (LG Display's hybrid in-cell/on-cell)

Sensor Structures…2

❖ Glass-only structures

Structure Names	GGG	GG or G-SITO	GG , G-DITO or G1G	OGS or SOC
Comments	Single ITO layer on each piece of glass; Obsolete	Single ITO layer with bridges	ITO layer on each side of 1 glass; or ITO on one side of 2 glass	Single ITO layer with bridges
Example Products	None	Kindle Fire, B&N Nook; Nokia Lumia 800	iPhone-1; iPad-1 (GG); Lenovo AiOs (G1G)	Google Nexus 4/7; Xiaomi 2; Nokia Lumia 920

Cover Glass	Cover Glass	Cover Glass	Cover Glass
Sense Electrodes	Drive & Sense	Sense Electrodes	Drive & Sense
Glass	Glass	Glass	
Adhesive		Drive Electrodes	
Drive Electrodes			
Glass			

- SITO = Single-sided ITO layer; usually means there's a bridge
- DITO = Double-sided ITO layer (Apple patent)
- OGS = One Glass Solution (sensor on cover-glass)
- SSG = Simple Sensor Glass (OGS without cover-glass shaping & finishing)

Sensor Structures…3

❖ Glass-and-film structures

Structure Names	G1F
Comments	Single ITO layer on glass; single ITO layer on film
Example Products	Many Samsung products in 2013; Microsoft Surface RT

- Why would a touch-module maker use a sensor structure that requires having both glass- and film-handling equipment?
  - » One reason is that there was a shortage of ITO film in 2013

Sensor Structures…4

❖ Film-only structures

Structure Names	GFF	GF2 or DITO-Film	GF1	GF Triangle
Comments	Bare glass and two single-sided ITO films; performance is better than GF1	Bare glass and one double-sided ITO film	Bare glass with true single-layer complex pattern on film (e.g., "caterpillar")	Bare glass with true single-layer triangle pattern on film (e.g., "backgammon")
Example Products	Samsung Galaxy Tabs and Notes; Google Nexus 10	Apple iPads; next iPhone if Apple can't get good yield on in-cell	Many low-end smartphones, especially in China	Low-end products with "gesture touch", not multi-touch

Cover Glass	Cover Glass	Cover Glass	Cover Glass
Sense Electrodes	Sense Electrodes	Drive & Sense	Sense Electrodes
Film	Film	Film	Film
Adhesive	Drive Electrodes		
Drive Electrodes			
Film			

- Single-layer caterpillar pattern is used to support "real" multi-touch with 2-3 touches, typically in a smartphone (that's not enough touches for a tablet)
- Single-layer backgammon pattern is used to support "gesture touch" on low-end devices, i.e., the ability to detect pairs of moving fingers but not always resolve two stationary touches

Sensor Structures…5

- **Why do touch-module makers choose one structure over another?**
  - Transmissivity
  - Thickness & weight
  - Border width due to routing
  - Cost & availability of ITO film or deposition
  - Lamination experience & yields
  - Existing equipment and/or method experience

Sensor Structure by Application

Smartphones

Structure	Share
GFF	42%
OGS/G2	16%
GF1/Single-Layer	12%
GG SITO	11%
GF Triangle	5%
GG DITO	5%
G1F	4%
PF	3%
PFF	2%

Tablets & Notebooks

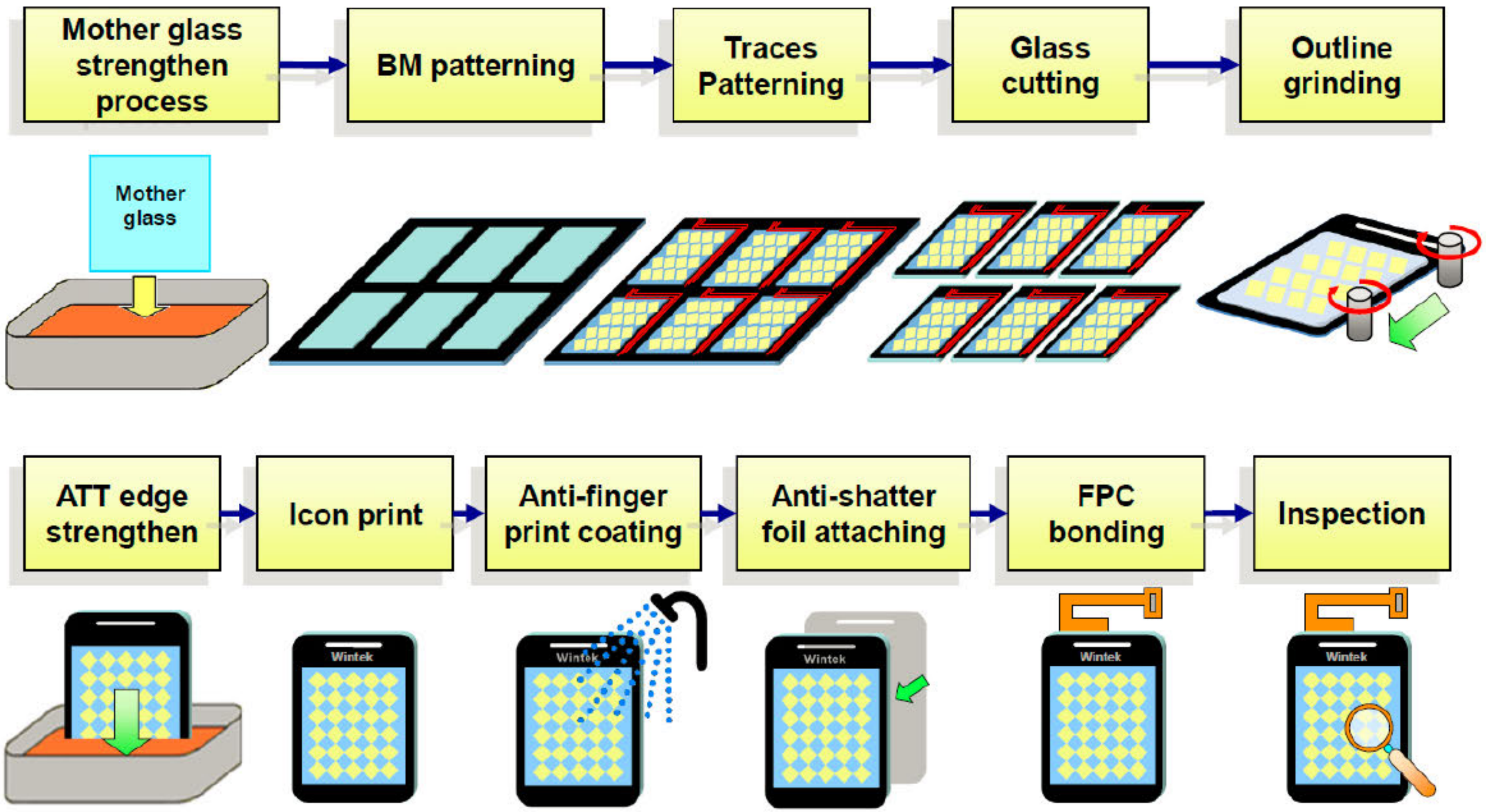
Structure	Share
GFF	44%
GF2/DITO Film	19%
OGS/G2	18%
GG DITO	11%
GG SITO	3%
G1F	2%
GF1/Single-Layer	1%
SSG	1%

All-in-Ones

Structure	Share
GG SITO	81%
GFF	13%
SSG	6%

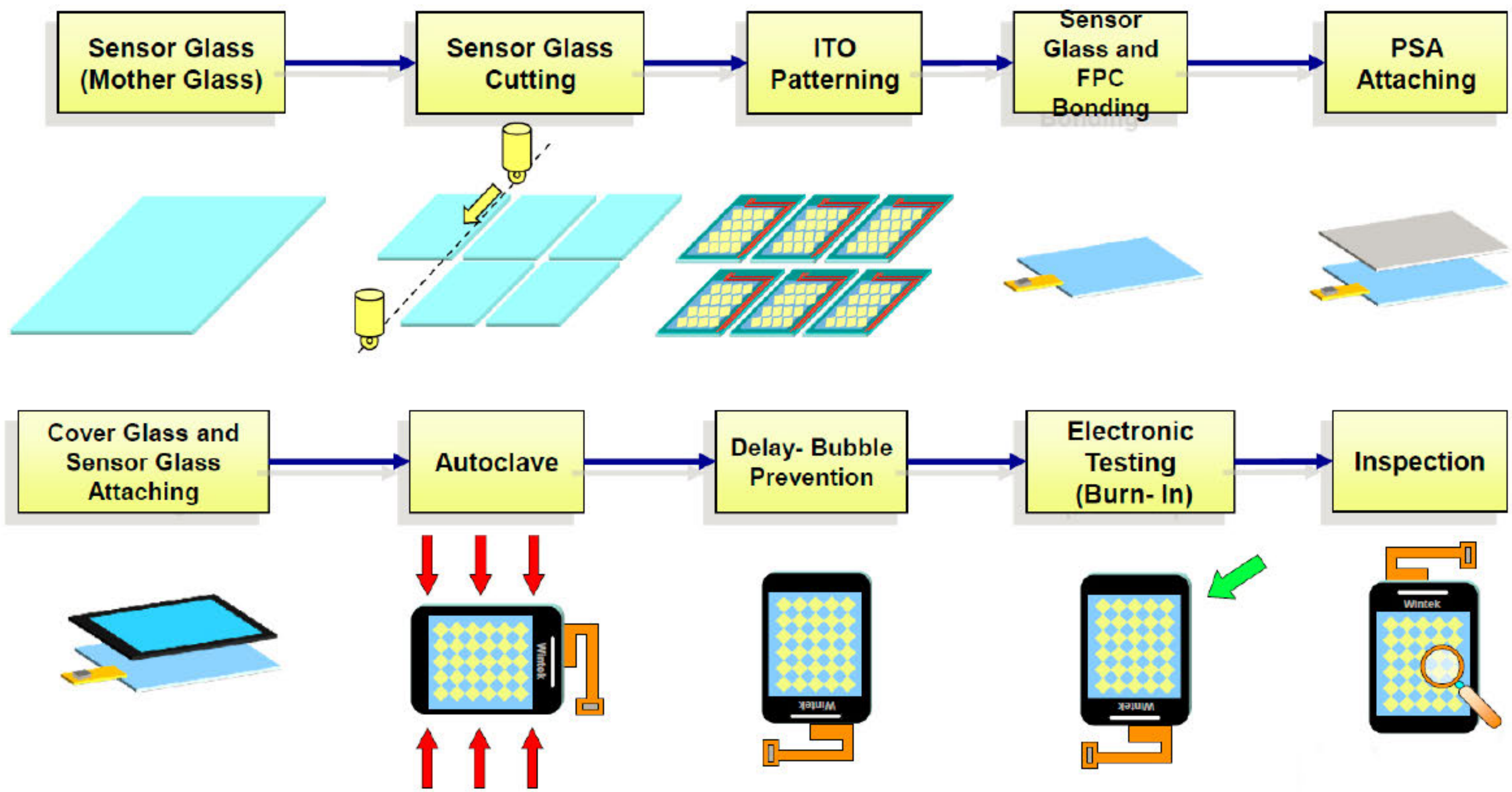
Data based on DisplaySearch's "Q1-2014 Quarterly Touch-Panel Market Analysis Report", with adjustments by the author

Sheet vs. Piece Method…1 (Wintek Sheet Example - OGS)



Source: Wintek

Sheet vs. Piece Method…2 (Wintek Piece Example - Discrete)



Source: Wintek

More On OGS

- **One-Glass Solution (OGS)**
  - Also called “touch on lens” (TOL), “sensor on cover” (SOC), “direct patterned window” (DPW) and <u>many</u> other names
  - Advantages
    - Eliminates a fourth sheet of glass (G-DITO), making the end-product thinner and lighter
    - Competitive weapon against embedded touch from LCD suppliers
  - Disadvantages
    - Requires close cooperation with cover-glass makers, or increased vertical integration (preferable)
    - Yields are lower (more complex operations)
    - Bendable cover glass can affect touch performance
    - Harder to shield touchscreen from LCD noise
  - **Note:** There is no generic name (yet) for touch sensors built on the cover-glass without direct ITO deposition (“OGS-type”)

Glass Strengthening

- **Heat strengthened**
  - Less-rigorous version of fully tempered; does not "dice" when broken; 2X as strong as standard glass
- **Fully tempered**
  - Uses heat; requires glass > 3 mm, so not used for consumer touchscreens; glass "dices" when broken (think auto windows); 4X to 6X as strong as standard glass
- **Chemical strengthened (CS)**
  - Uses ion-exchange in a salt bath; best for glass < 3mm; glass does NOT "dice" when broken; 6X to 8X as strong as standard glass
- **High ion-exchange aluminosilicate glass**
  - 6X to 8X as strong as standard glass (same as CS glass)
  - Corning Gorilla®, Asahi Dragontrail™, Schott Xensation™

Sensor Surface Treatments…1

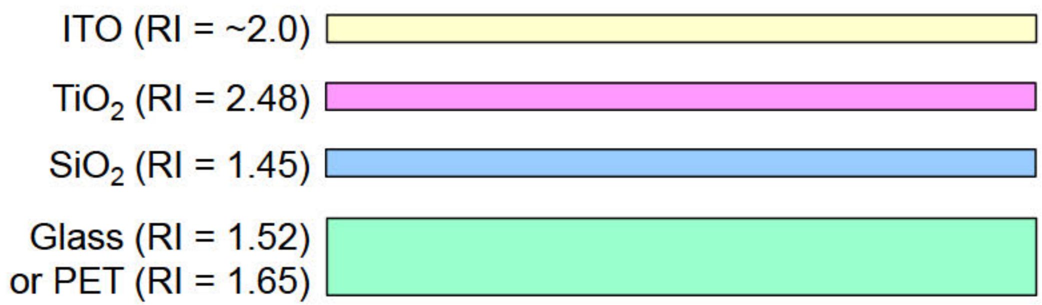
- **Historically most common treatment is anti-glare (AG)**
  - Changes specular reflection into diffuse reflection
  - Used mostly for commercial & enterprise, not consumer (“glossy”)
  - Three methods, roughly equal cost
    - Chemical etching
    - Application of sol-gel containing silica particles
    - Mechanical abrasion
  - Level of anti-glare can be very little to a lot
- **Anti-fingerprint (AF) treatment is rapidly growing**
  - Many different forms (spray-on, rub-on, sputter, etc.); also called “anti-smudge” (AS)
  - Demand is increasing
  - Cost is dropping (currently ~$8.50/m^2)

Sensor Surface Treatments…2

- **Anti-reflection (AR) treatment is still a problem**
  - Reduces specular reflection to range of 2% to 0.4%
  - Durability is typically < 1 year
  - It's expensive (currently ~$34.50/m^2)
  - Yet it's really important for outdoor viewing, particularly of consumers' glossy screens (ideal is AF+AR = ~$43/m^2)
- **Other coatings are available but less common**
  - Anti-corruption (allows permanent Sharpie ink to be wiped off)
  - Anti-microbial/anti-bacterial (AM/AB, for healthcare applications)
  - Hard coating (can be made up to 9H for glass-like anti-scratch)
  - Anti-stiction (reduces finger-sticking friction)
  - Anti-crack coating (increases durability at lower cost than Gorilla glass; uses atomic layer deposition [ALD])

ITO Refractive-Index Matching

- **Reduce the reflectivity of ITO by compensating for the difference in index of refraction of ITO vs. glass/PET**
- **Limited to 2 layers on PET; more can be used on glass**
  - Alternating layers of material with low and high refractive index
  - Layer thicknesses (typically between ¼ and ½ of the wavelength of light) are chosen to produce destructive interference in reflected light, and constructive interference in transmitted light



Source: The author

Sensor Suppliers

- **Many touch-module makers manufacture their own sensors**
  - The remainder are made by the following companies, in order by estimated 2013 revenue

Company	Country
Nissha Printing	Japan
HannsTouch	Taiwan
Dongwoo Fine Chemical	Korea
Cando	Taiwan
Innolux	Taiwan
CSG	China
Token	China
CPT	Taiwan
DNP	Japan
Young Fast	Taiwan
AimCore	Taiwan

And at least one more…

- Laibao (China)

ITO-Replacement Materials

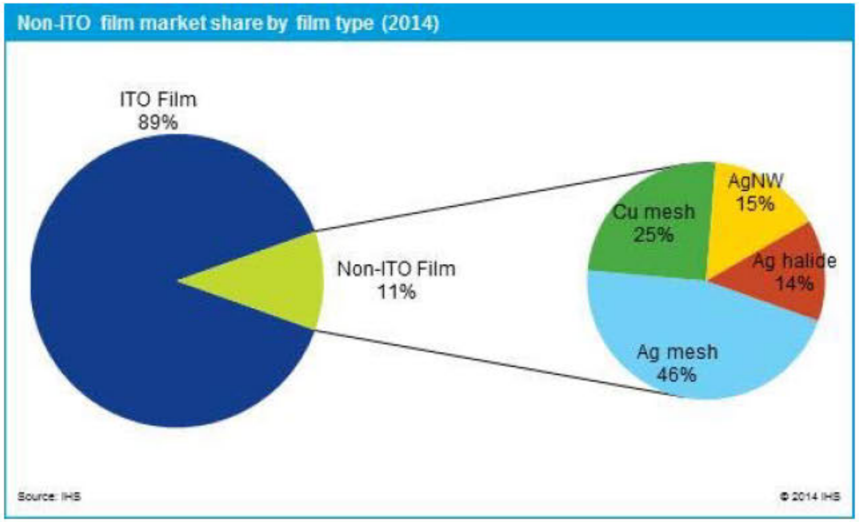
- ITO
- Metal Mesh
- Silver Nanowires
- Carbon Nanotubes
- Conductive Polymers
- Graphene
- Summary

ITO Replacements…1

- **Why replace ITO?**
  - **Costly to pattern & needs high temperature processing**
  - Highly reflective (IR = 2.6) & tinted yellow; brittle & inflexible
  - **NOT** because we're going to run out of it!
- **Replacement material objectives**
  - **Solution processing (no vacuum, no converted LCD fab)**
  - Better performance than ITO (transmissivity & resistivity)
  - Lower material & process cost than ITO
- **Five replacement candidates**
  - Metal mesh
  - Silver nanowires
  - Carbon nanotubes
  - Conductive polymers
  - Graphene

ITO Replacements…2

- **ITO-replacement materials are having a definite market impact – 11% in 2014!**
  - See the latest IHS market report on non-ITO films



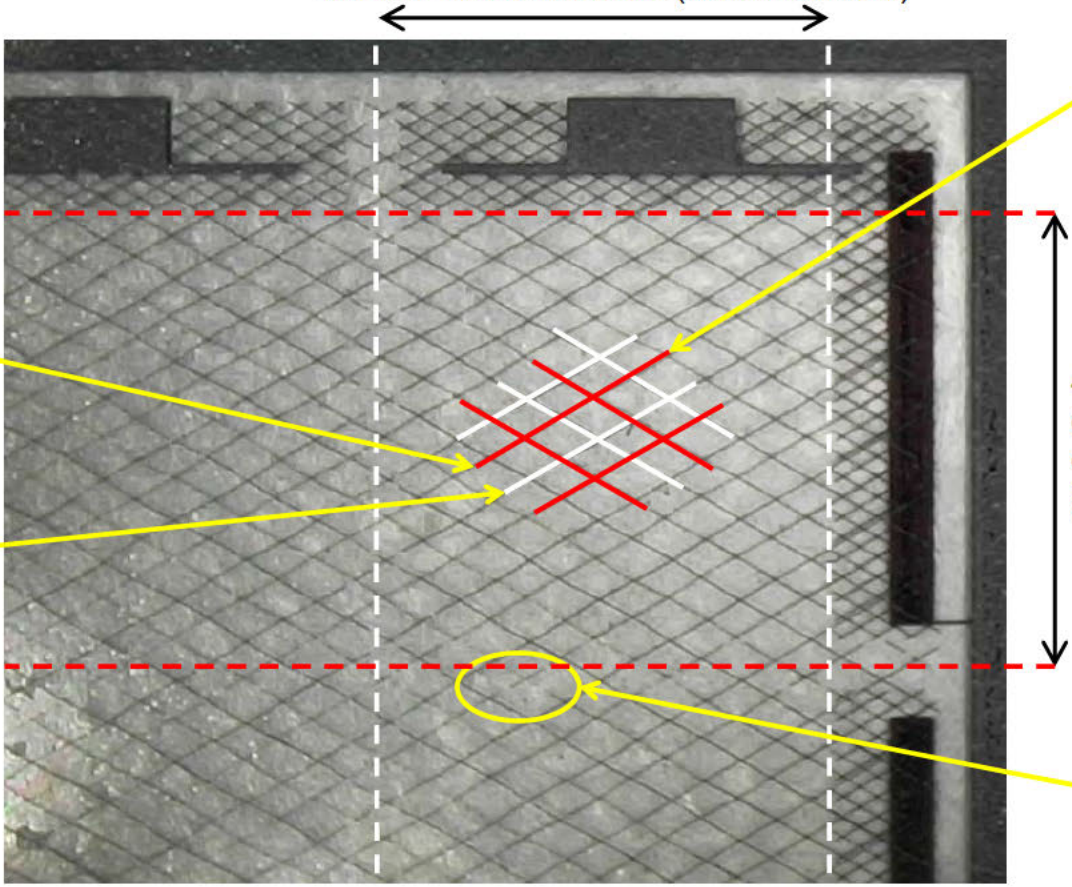
- Ag halide is simply another method of making a silver mesh, so the mesh total is 85% vs. 15% for nanowire

  - The value is performance and cost
    - Both unit cost and CAPEX

Metal Mesh…1

- **Metal mesh is shipping in touchscreens, and it's looking very promising!**
- **Brief history of first-movers**
  - **MNTech** in Korea was the first to ship metal-mesh at the end of 2012 – but their factory burned down
  - **Atmel** (partnered with CIT in the UK) was the second to ship metal-mesh (XSense™) for a smartphone and a 7" tablet in 1H-2013
  - **FujiFilm** started production of their silver-halide-based metal-mesh product in 2Q-2013

Metal Mesh…2



Source: Photo by Unipixel, annotation by the author

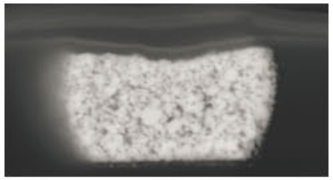
Metal Mesh…3

- **Metal mesh has significant advantages**
  - Patterning via roll-to-roll printing allows both operating and capex cost to be very low – it's going to beat both litho and laser!
    - Electrodes and border connections are printed simultaneously, which allows borders as narrow as 3 mm (typically 9 mm with ITO)
  - Sheet resistivity is much lower than ITO (**under 10 ohms/square**)
    - Reduces p-cap charge time, which allows larger touchscreens
  - Transparency is better than ITO
  - Mesh pattern creates electrical redundancy, which improves yields
  - Highly flexible – bend radius typically 4 mm

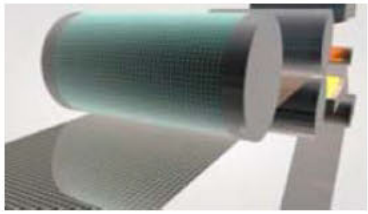
Metal Mesh…4

- O-film is the "800-pound gorilla" of metal mesh!
  - Largest touch-module maker in China, #3 globally
  - Like "the TPK of film"; innovative and aggressive
- New roll-to-roll printing method
  - "Hybrid printing" or "micro-imprinting"

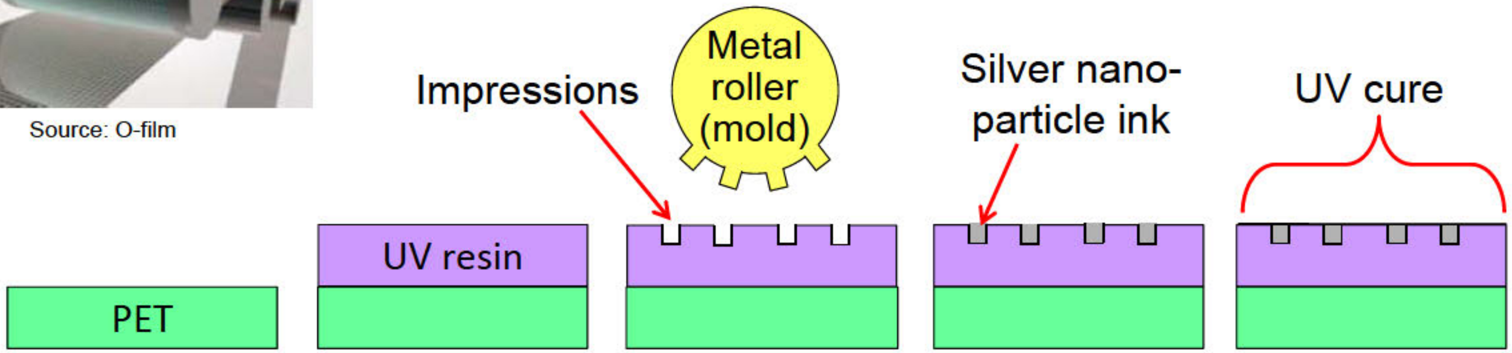
Source: O-film



Cross-section of embedded metal line



Source: O-film

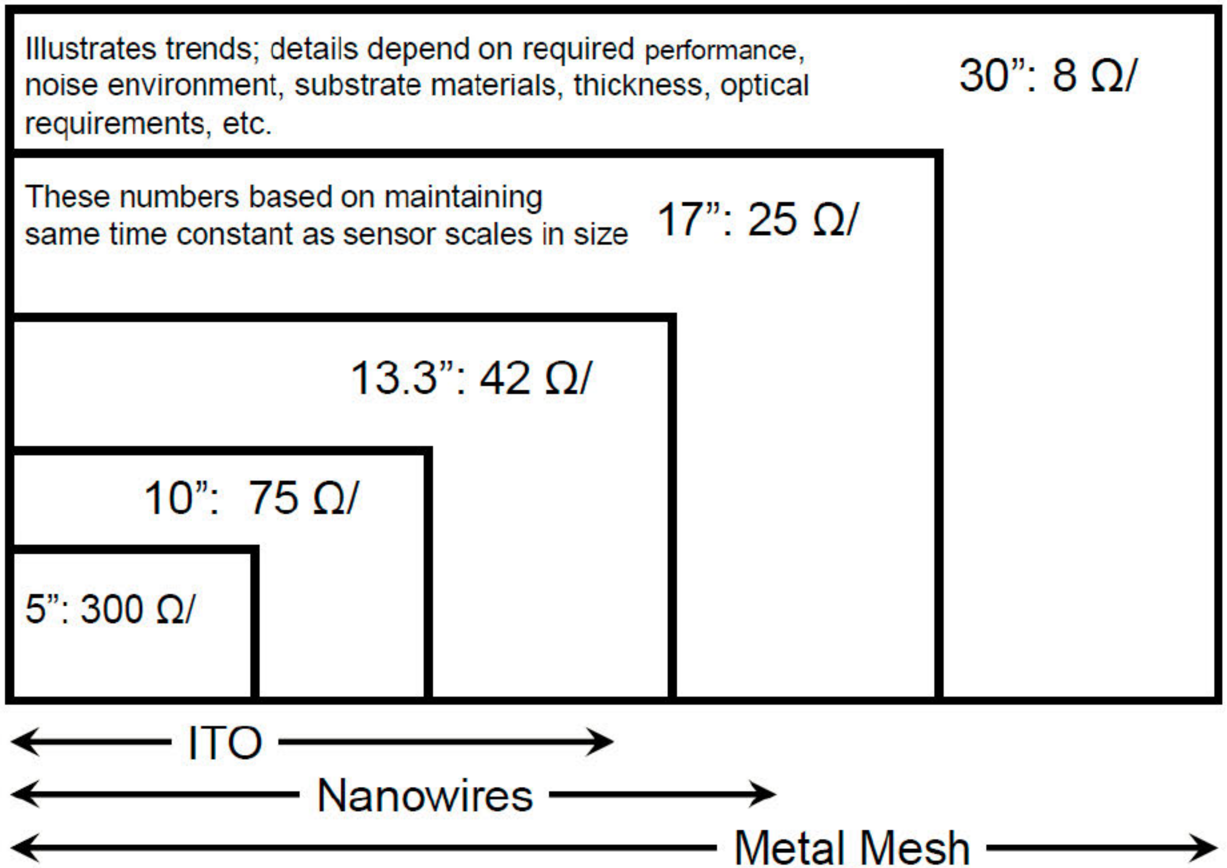


Source: The author

Metal Mesh…5

- **O-film technical details**
  - Additive process with little waste
  - **< 2 μm line width**
  - < 10 Ω/□
  - Randomized mesh design (one method of eliminating moirés)
  - Top surface of embedded metal line is blackened & sealed
  - Embedded metal reduces haze and eliminates peel-off
  - Producing > 1.5M touch sensors per month (size not stated)
- **O-film's success makes visible a developing aspect of the ITO-replacement business**
  - A vertically-integrated sensor & module-maker is in a much better position to profit from ITO-replacements than a film-only supplier, or (even worse), an ink-only supplier

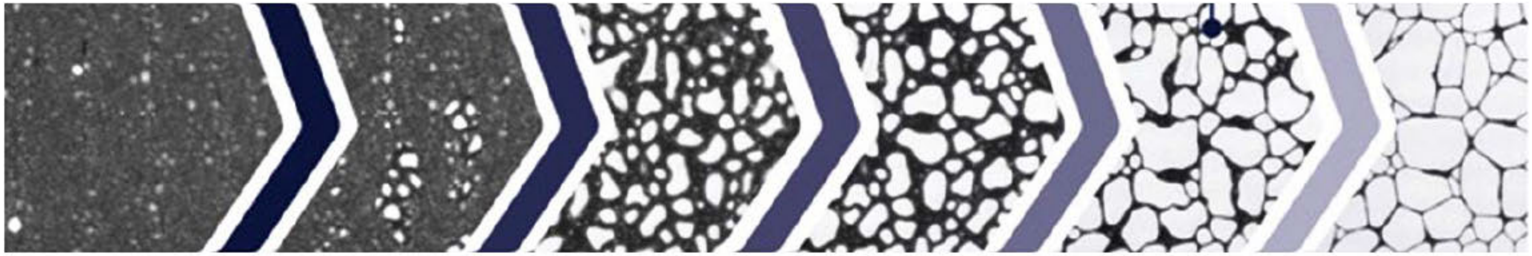
Synaptics' Opinion of Sheet Resistivity Requirements



Source: Synaptics (unmodified)

An Interesting Variation on Silver Mesh…1

- **Cima NanoTech**
  - "Self-assembling" silver mesh
  - Starts with an opaque liquid coated on film with standard equipment
  - 30 seconds later it dries into a random-pattern silver mesh



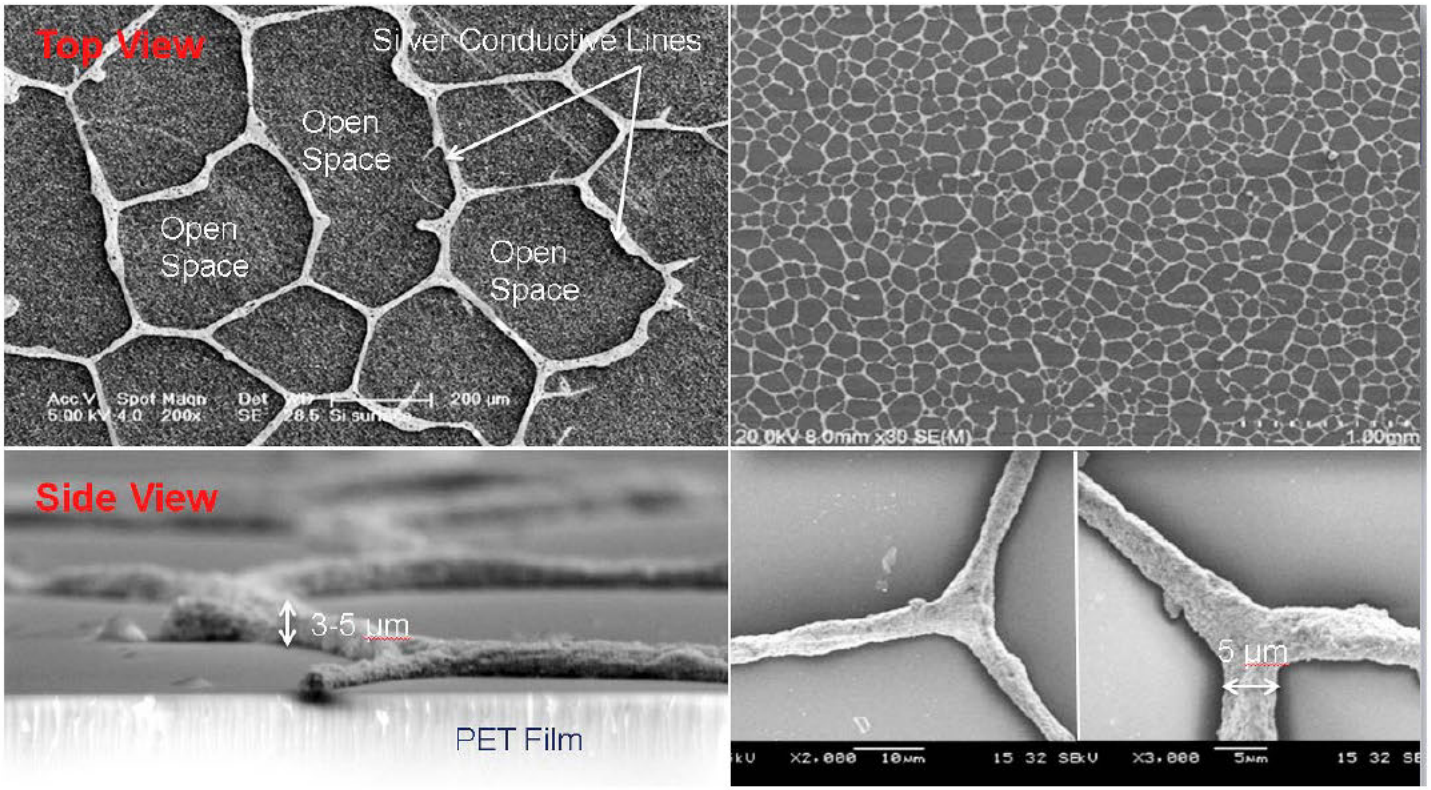
Drying sequence

Source: Cima NanoTech

- **Pros:** Simple, standard wet-coating process; no moiré (due to randomness); very good for large-format touch
- **Cons:** It's just a uniformly-coated film that must be patterned with a laser or other method

An Interesting Variation on Silver Mesh…2

- Cima NanoTech continued…



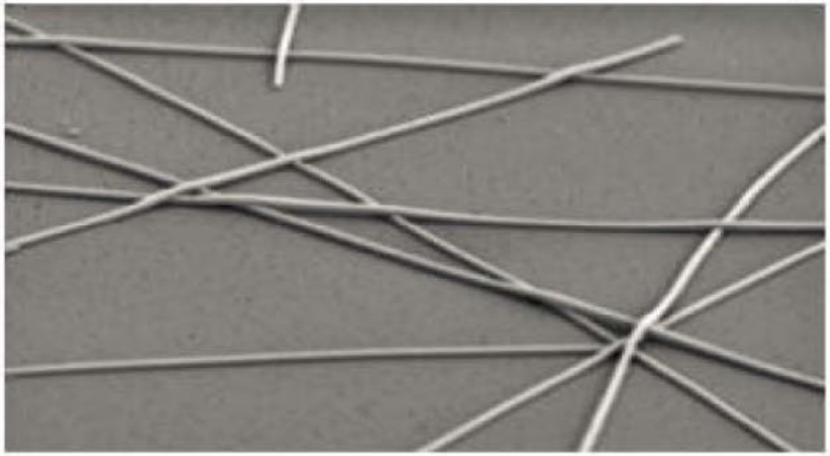
Source: Cima NanoTech

Silver Nanowires…1

- **Cambrios is the first-mover and clear leader**
  - Other suppliers include Carestream, Blue Nano, Poly IC, etc.

Plan view

70° view

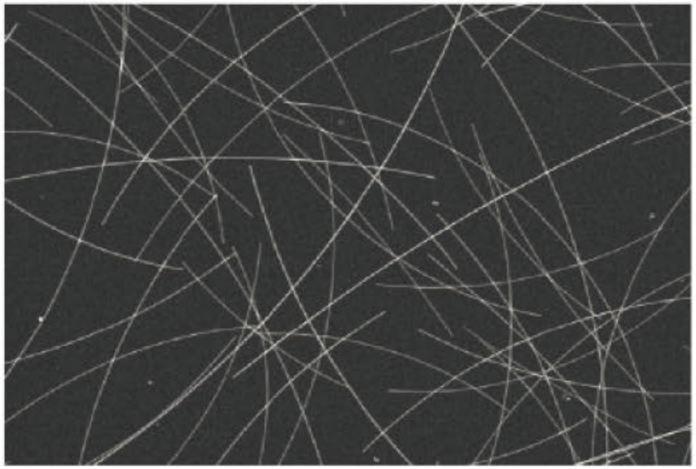


Source: Cambrios

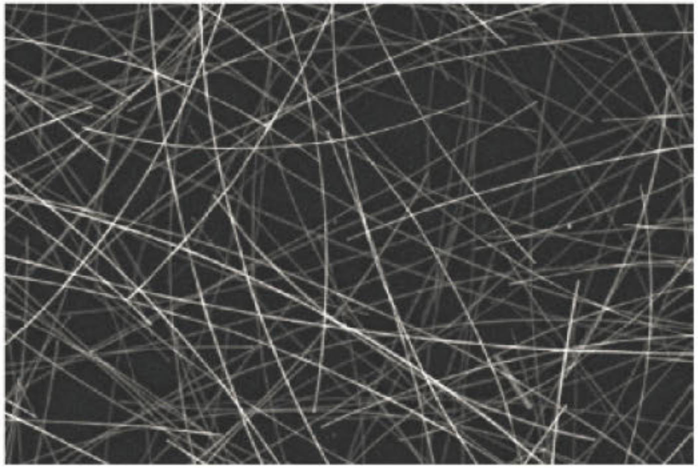
Silver Nanowires…2

❖ **Density determines sheet resistance, independent of coating throughput**

70 Ω/□



9 Ω/□



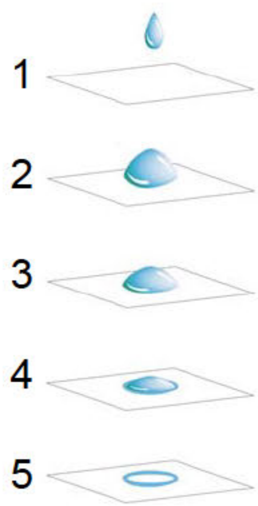
Source: Cambrios

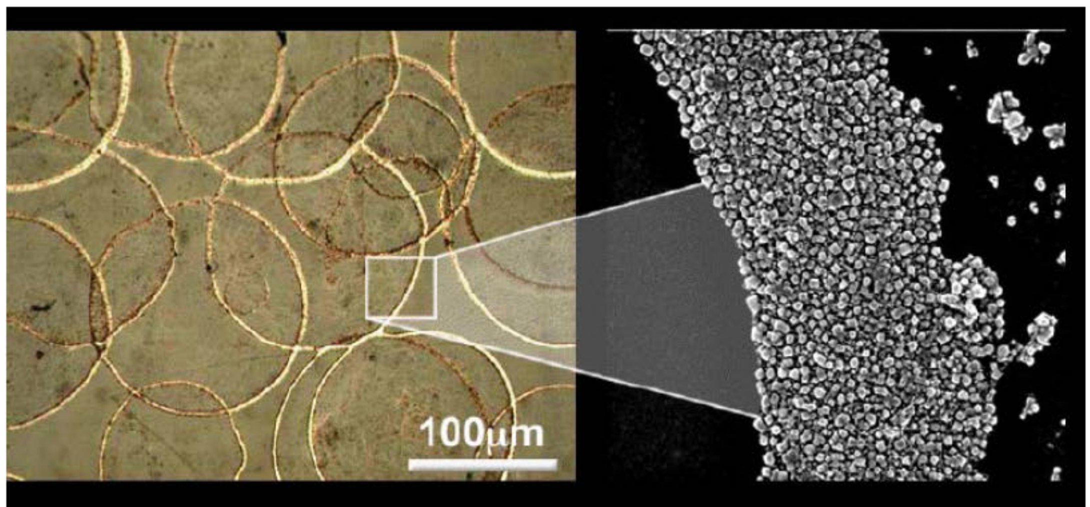
Silver Nanowires…3

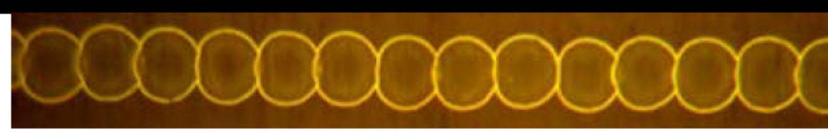
- **Advantages**
  - High conductivity (10 Ω/□ at 94% transmission)
  - High transparency
  - Can be spin-coated or slit-coated (printing is under development)
    - TPK + Cambrios + Nissha joint venture
  - Nano-scale, so no visibility or moiré issues
  - Shipping in products from phones to all-in-ones
    - Same sensor for different pixel densities (unlike metal-mesh)
  - Established supply chain
    - Film makers: Okura, Hitachi Chemical, Toray, DIC, ShinEtsu, LGE, etc.
    - Module makers: eTurboTouch, LGE, Nissha, CNi, ShinEtsu, etc.
- **Disadvantages**
  - Increased haze at < 30 Ω/□
  - Cambrios' positioning as an ink supplier (far down the food chain)

An Interesting Variation on Silver Nano-Particles

- **ClearJet (Israel)**
  - Inkjet-printing silver nano-particle drops < 10 µm thick
  - Ink dries from center outward, leaving "coffee rings" ~100 µm
  - 95% transparency, 4 ohms/square resistivity



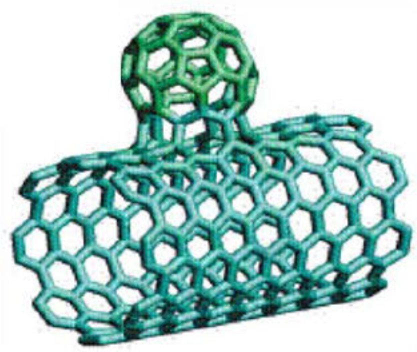


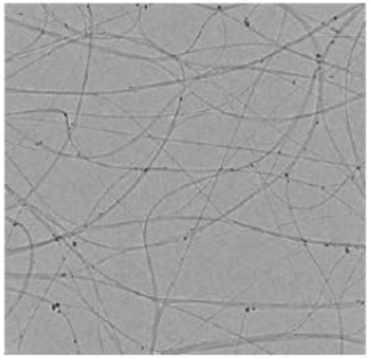


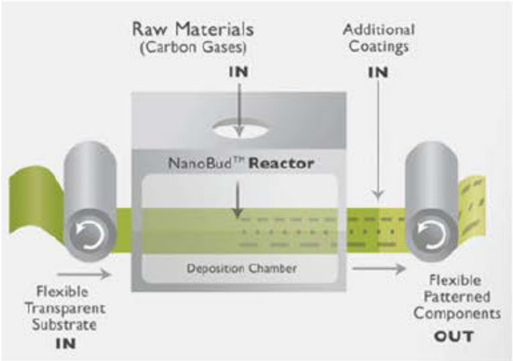
Source: ClearJet

Carbon Nanotubes

- **Carbon NanoBuds™ by Canatu (Finland)**
  - "NanoBud" = nanotubes + bucky-balls (C_{60} fullereens)
  - Probably the best current bet on CNTs, with moderate-volume production by the end of 2014
    - Better optical performance than silver nanowires
      - Very low reflectivity and lower haze
    - More flexible (bend radius 0.5 mm!)
    - Note that the "NanoBud Reactor" is a multi-step process that includes (1) deposition of CNTs, and (2) laser patterning







Source: Canatu

Conductive Polymers & Graphene

- **Conductive Polymers (PEDOT:PSS)**
  - Kodak (partnered with Heraeus) is the leader; AGFA is trailing
  - First shipments of actual sensors began in 1H-2014
  - Resistivity isn't much different from ITO, but it's easy to apply (e.g., with screen printing)
    - White-goods manufacturers can use it to make their own touch control panels in appliances (for example)
- **Graphene – it hasn't started in touchscreens yet**
  - Like unrolled carbon nanotubes, a one-atom thick sheet
    - Promising strength, transparency, and conductivity, but development is still in its infancy – and there are so many other hot applications for the material than touchscreens!
  - Resistivity, transparency, manufacturability just aren't there yet

ITO Replacements Summary…1

- **Current realities**
  - It's about the ITO in touchscreens, not in LCDs
    - ITO used in LCDs is 1-2% of cost (~$4 for a 40" display)
    - LCD makers are extremely reluctant to make changes in fabs
  - It's not really about flexible displays, at least not yet…
  - It's not really about the indium supply or cost
  - It's about the processes that ITO requires, not about ITO itself
    - The dominance of patterned-ITO touchscreens (p-cap) over uniform-ITO touchscreens (resistive) has drastically changed the picture
  - Mesh and silver nanowires are the main competitors, and mesh seems to be taking a strong lead
  - This entire market has come alive exceptionally quickly!

ITO Replacements Summary…2

- **Predictions**
  - Most current capital-intensive, glass (fab)-based, p-cap module suppliers are going to be in a world of hurt because they have to maintain a targeted return on their LARGE invested capital
  - Film-based module suppliers (formerly second-class citizens) will become the leaders of the touchscreen industry
  - Five years from now, more than 50% of p-cap sensors will be made using an ITO-replacement material
  - 10 years from now, p-cap fabs will be like many passive-LCD fabs today (fully depreciated and unused)

Modules

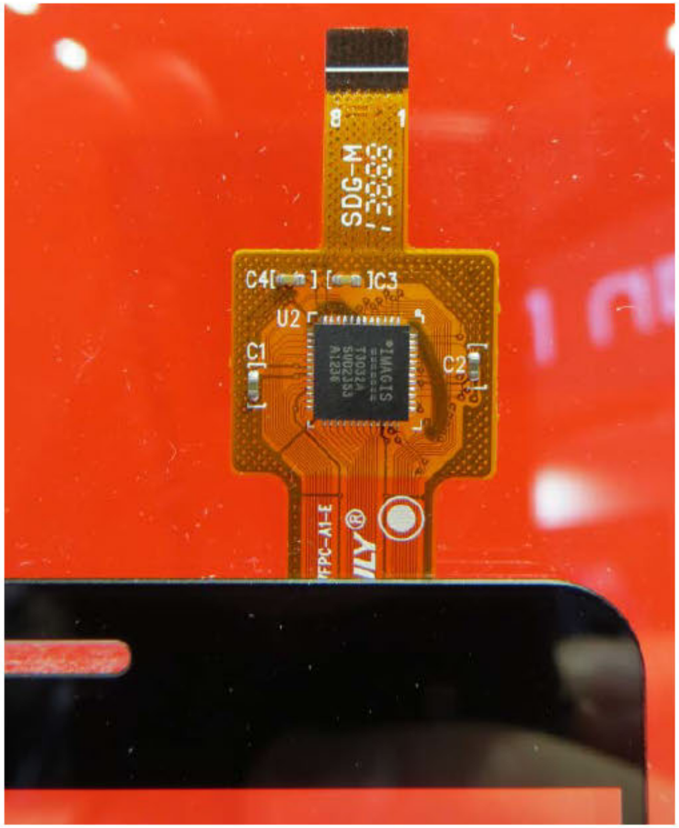
- Routing Traces
- Tail & ACF
- Cover Glass
- Lamination & Bonding
- Integration Into a Device
- Commercial Markets
- Touch System
- Advantages & Disadvantages
- Suppliers

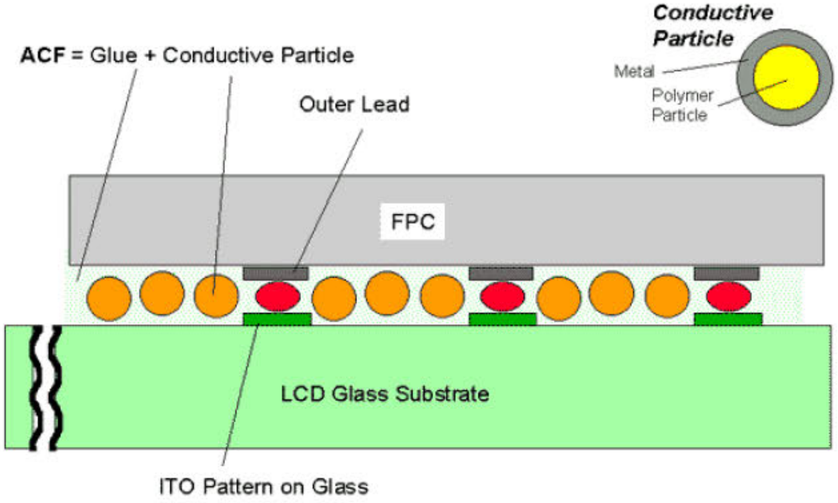
Routing Traces

- **Sensor electrode connection traces**
  - Narrow borders are the driving force
  - Glass sensors use photolithography to pattern the connection traces; “double routing” (stacking) makes even narrower borders
  - Film sensors historically used screen-printing for both the electrodes and the connection traces; many film sensor-makers are buying photolithography equipment for the traces

Tail & ACF

❖ **FPC with controller and ACF**





Cover Glass…1

- **Cover-glass types**
  - Soda-lime
  - Chemically strengthened (CS)
  - Ion-exchange strengthened (e.g., alumino-silicate)
- **Minimum cover-glass thickness (0.4 mm today) is driven by two factors**
  - Durability (resistance to damage, especially with bezel-less design)
  - Capacitive-sensing limitations when the device is ungrounded

Cover Glass…2

- **Cover-glass processing**
  - Forming
  - Decorating
  - Coating (AR, AG, AF, AC, AB…)
- **Plastic cover-glass**
  - It hasn't really happened yet
  - Deformability is a big problem (bigger than scratching)

Lamination & Bonding

- **Lamination (film to glass, or film to film)**
  - Yield is key

- **Bonding (touch module to display)**
  - Direct bonding = No air-gap, spaced filled with solid (OCA) or liquid (OCR) adhesive
  - "Air bonding" = Air-gap (gasket around periphery)

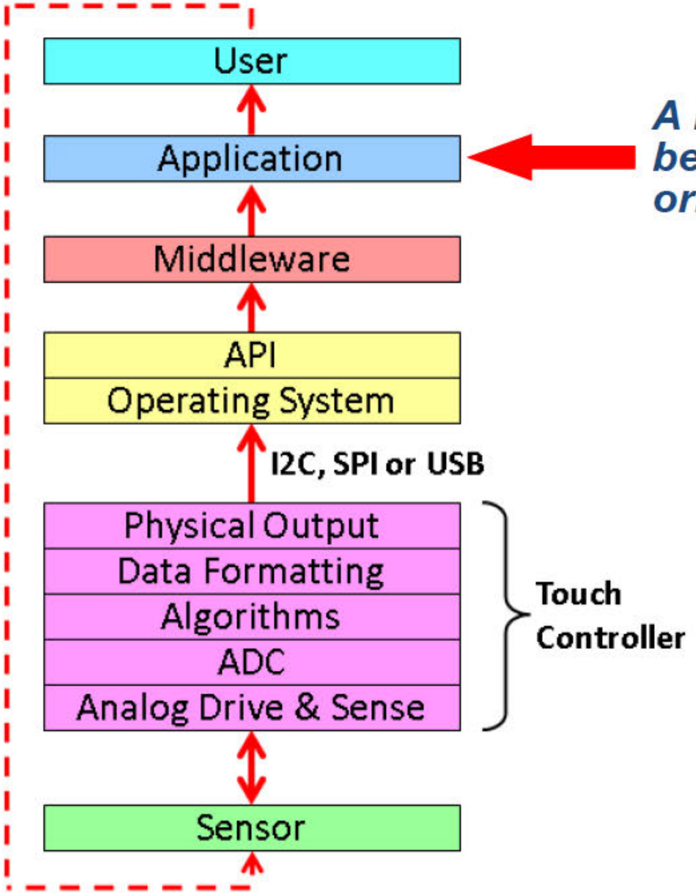
Integrating P-Cap Into a Device

- **After the mechanical & industrial design are done, it's really all about just one thing: "Tuning"**
  - Every new product must have the p-cap touch-screen controller "tuned" to account for all the variables in the configuration
    - Basic configuration (e.g., OGS vs. embedded)
    - Sensing pattern
    - Glass thickness
    - Adhesive thickness
    - LCD noise
    - LCD frame mechanics
    - Air-gap or direct-bonded… etc.
  - All controller manufacturers either supply tools (e.g., Synaptics' "Design Studio 5") or they do it themselves for their OEM customers
  - Initial tuning can take more than a full day of engineering time

Commercial Markets

- **Adoption of P-Cap Into Commercial Markets (Forecast)**
  - Healthcare – Rapid, within FDA-cycle constraints
    - Buying for the future with a very long product life
    - Zero-bezel, multi-touch, light touch are all important
  - Gaming – Rapid, within gaming regulation constraints
    - Casinos want to attract the Millennium Generation
    - Multi-touch is very important; zero-bezel is less so
  - Point of Information – Moderate
    - Software-driven; zoom gesture could be the key
  - Industrial – Slow
    - Multi-touch may be important; zero-bezel & light touch are less so
  - Point of Sales – Very slow
    - Zero-bezel is the only driver; "flat-edge resistive" is good enough

Touch System…1



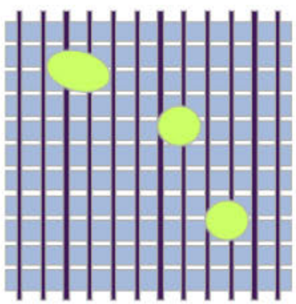
A lot of bad touch behavior actually originates here!

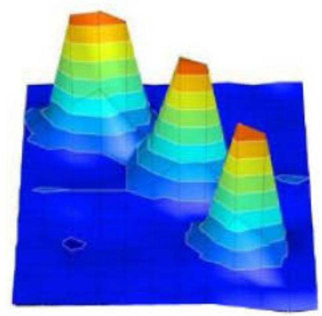
You don't believe it?

*Download "**Touch Explorer**" by Synaptics from Google Play and see if you can make your touchscreen fail to respond properly*

Touch Processing

- Control sensor electrodes to generate raw data
  - Noise avoidance via multiple techniques: Frequency Shifting, CDM, etc…
- Process data to convert to Image data
- Derive and report data about finger touches (position, width, gestures)





$(x, y, w, z)_1$

$(x, y, w, z)_2$

$(x, y, w, z)_3$

Data Acquisition

- Tx signals generated
- Rx conversion via A/D
- Noise avoidance

Frame Processing

- Collect and Scale Capacitance
- Remove Common Mode Noise
- Gain Compensate
- Apply Thresholds

Object Processing

- Segmentation
- Track Objects
- Classify Objects
- Calculate and Report Positions

Source: Synaptics

Computer Actions: Gesture Processing

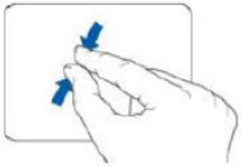
Tap and Double Tap.
- Light touch action – selects application

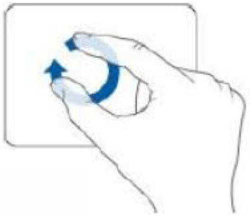
Flick
- Next Page of Icons, Fast directory search, Next Photo etc. ..

Scrolling
- Slider for message forward, volume, contrast, directory search control etc..

Proximity detection
- LCD screen wake up

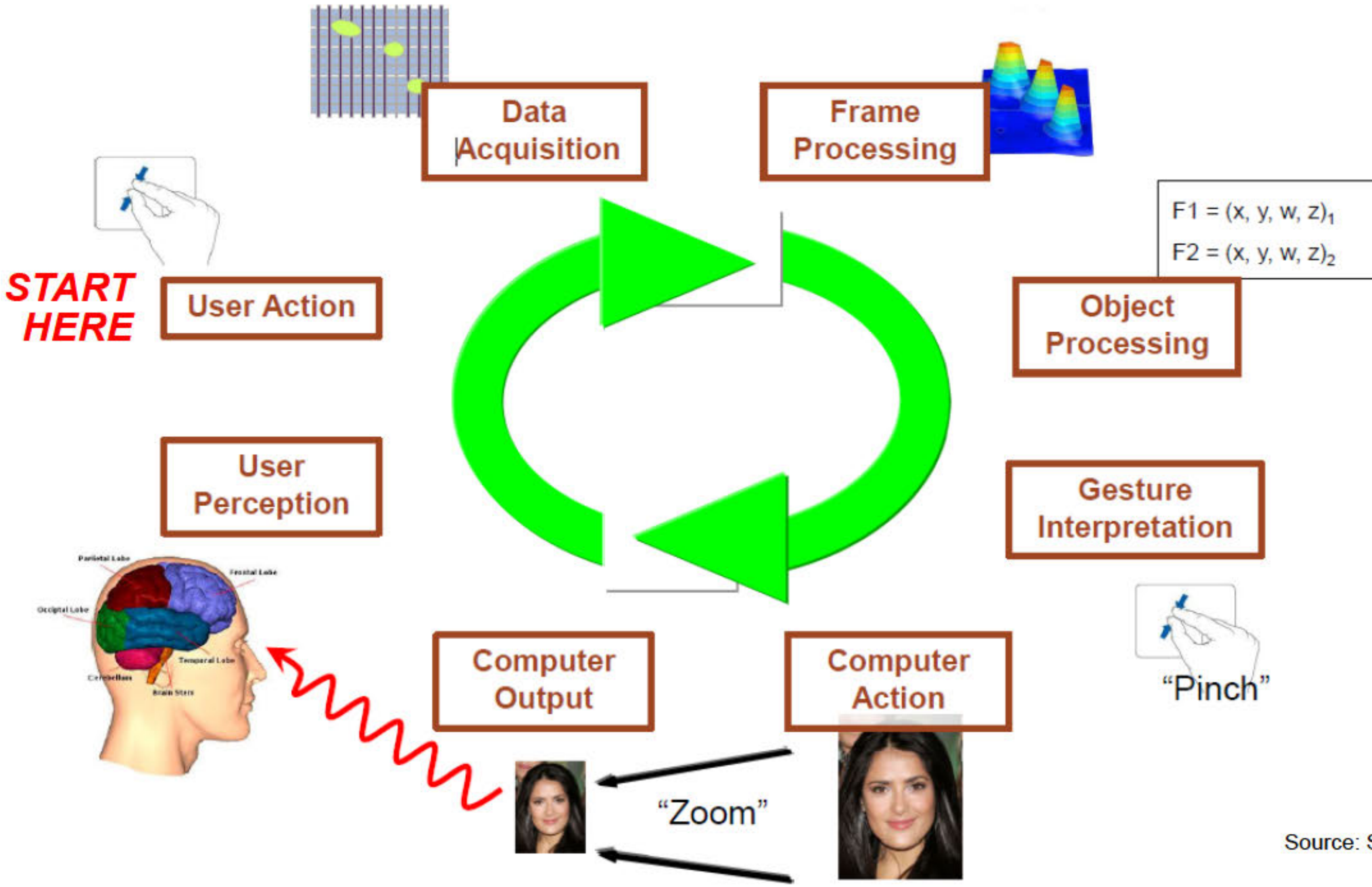
Multi Finger gestures
- Pinch for zoom
- 2 Finger rotate (photo rotate)
- Two finger flick
- Bring up new menu
- Simple games





Source: Synaptics

Human in the Loop



Source: Synaptics

Touch System…2

- **Controller output data**
  - Windows (USB): HID packets
  - Android (I2C or SPI): Vendor-defined format
- **OS processing**
  - Built-in gesture recognition
  - Custom gestures
- **Middleware example**
  - MyScript (formerly Vision Objects) in Samsung Galaxy Notes

P-Cap Advantages & Disadvantages

P-Cap Advantages	P-Cap Disadvantages
Unlimited, robust multi-touch (if properly implemented)	Still relatively high cost, although it is dropping – especially in notebook sizes
Extremely light touch (zero pressure)	Touch object must have some amount of capacitance to ground (or active stylus)
Enables flush touch-surface (no bezel)	Challenging to integrate ("tuning")
Very good optical performance (especially compared with resistive)	Difficult to scale above 32" with invisibility
Extremely smooth & fast scrolling (if properly implemented)	No absolute pressure-sensing; only relative finger-contact area
Durable touch surface not affected by scratches and many contaminants	
Can be made to work with running water on the surface	
Can be made to work through extremely thick glass (~20 mm)	
Can be sealed to NEMA-4 or IP65	

Module Suppliers (Discrete & Embedded)

Supplier	Share
Samsung Display	13.1%
TPK	8.9%
O-film	7.8%
GIS	5.6%
ECW EELY	4.8%
Japan Display	4.4%
Sharp	4.0%
Truly	3.0%
Others	3.0%
Melfas	3.0%
LG Display	2.7%
SMAC	2.5%
Iljin Display	2.3%
ALPS Electric	2.1%

Supplier	Share
LG Innotek	2.0%
Wintek	2.0%
Laibao	1.7%
EACH	1.6%
Lcetron	1.6%
Top Touch	1.6%
Mutto Optronics	1.5%
ELK	1.5%
Synopex	1.4%
Young Fast	1.3%
Digitech Systems	1.3%
Panasonic	1.1%
Goworld	1.1%
JTouch	1.0%

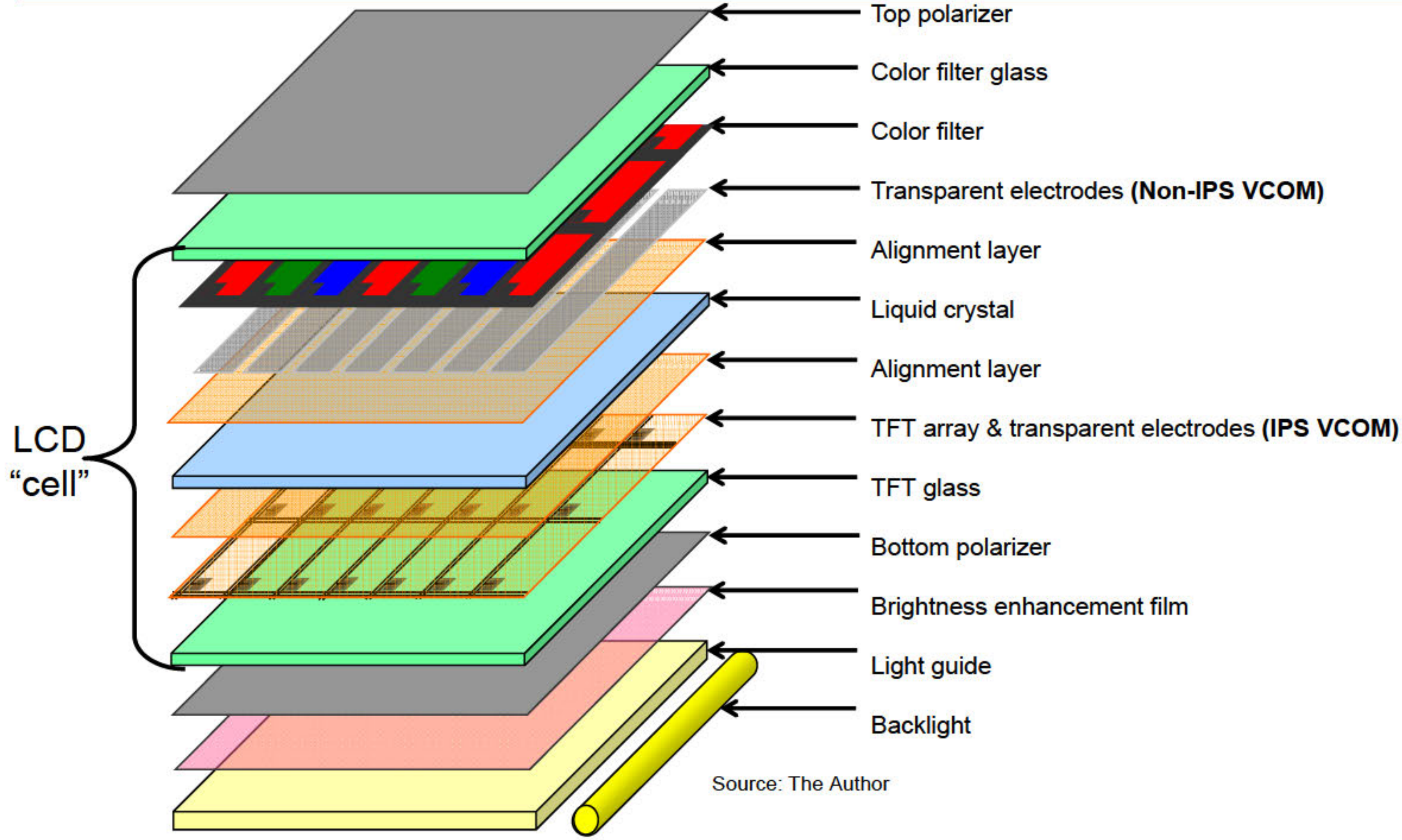
- 35% of suppliers account for 88% of units

Source: DisplaySearch Touch-Panel Market Analysis Report 1Q-2014

Embedded Touch

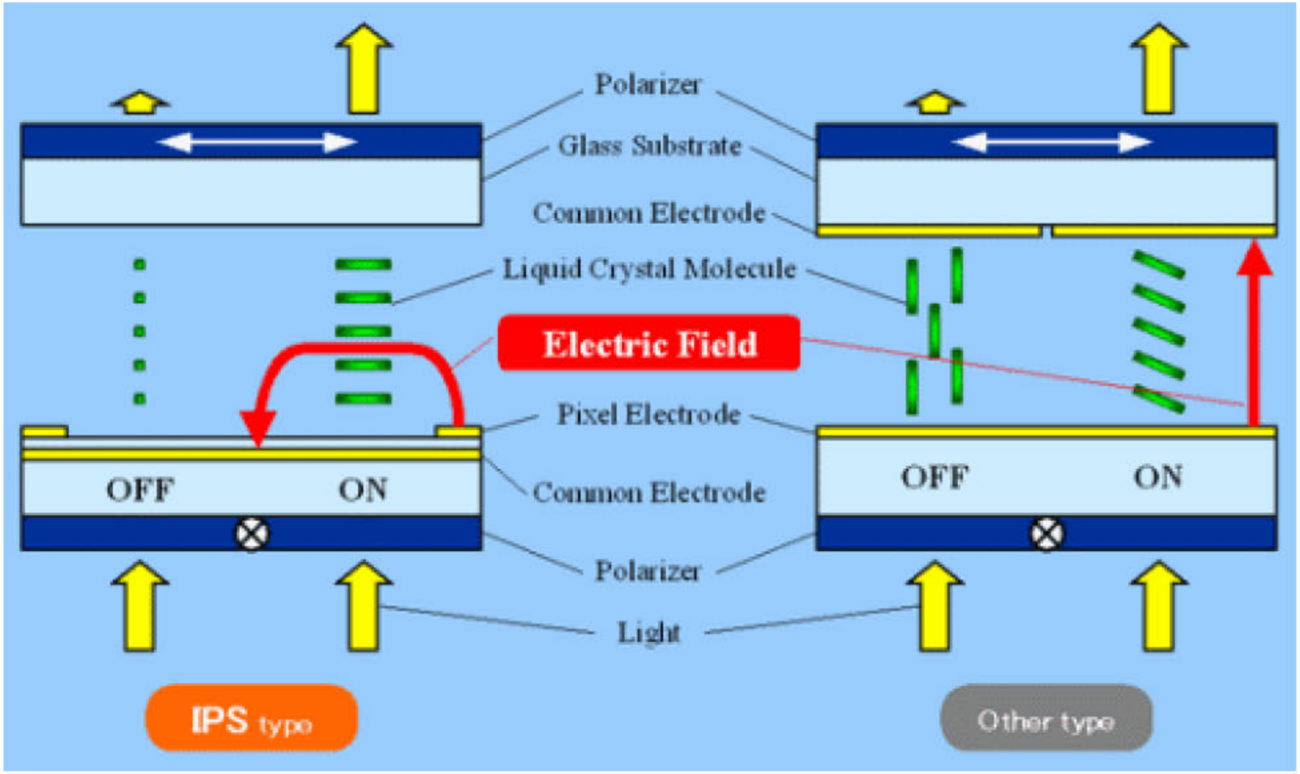
- LCD Architecture Refresher
- Embedded Terminology
- Early Embedded Failures
- On-Cell P-Cap
- Hybrid In-Cell/On-Cell P-Cap
- In-Cell P-Cap
- Summary of Sensor Locations
- Integrating the Touch Controller & Display Driver
- Discrete Touch vs. Embedded Touch

LCD Architecture Refresher



Source: The Author

IPS vs. Other LCD Architectures



Source: Presentation Technology Reviews