Monolithic Instruments

(New opportunities for wafer fabs)

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Outline

- Trend in Manufacturing and Instrumentation
- Definition of Monolithic Instruments
- Examples
    - Elevated Photodiode Arrays
    - OLED Microdisplays
    - Digital Micromirrors
- Manufacturing/Integration Challenges
- Future Opportunities

Product Trends

- **Instrumentation**
  - Reduced system size.
  - Increased computational power.
  - Increased operational speed.
  - <u>Improved levels of process control</u>.
  - Improved reliability of manufacturing systems.
  - Reduced system cost.
- **Integrated Circuits**
  - Reduced system size.
  - Increased computational power.
  - Increased operational speed.
  - Reduced transducer size.
  - Novel solid-state transducers/actuators.
  - Reduced system cost.

Largely Enabled by Integrated Circuits!

Semiconductor Manufacturing

- **Current Manufacturing Tolerances**
  - **Wafer flatness: < 100nm across a 300 mm wafer.**
  - **Metal impurity concentration: $< 1 \times 10^{10}$ cm^{-3}.**
  - **Stacking fault density: < 1/cm^2.**
  - **Layer-to-layer alignment tolerance: < 25 nm.**
  - **Linewidth control: 3 nm 3σ.**
  - **Minimum feature half-pitch: 100 nm.**
  - **Film thickness control: < 4% 3σ over 300 mm.**
- **Current typical high-volume CMOS device specs.**
  - **Transistor Density: ~9×10^7 transistors/cm^2.**
  - **Operating Frequency: ~1.7 GHz.**
  - **Manufacturing Cost: ~ $32/$cm^2$.**
    - **$3.6x$10^{-7}$/FET**

Value of a Semiconductor Mfg. Platform

	Semiconductor Mfg	Machining Mfg	Mach./Semi.
Minimum Feature Size	0.25 µm	100 µm	400:1
Alignment Tolerance	< 25 nm	~ 10 µm	40,000:1
Manufacturing Cost	$\$1 \times 10^{-6}$/FET	~$\$2 \times 10^{-1}$ /switch	200,000:1

For the number of devices made, a <u>semiconductor fab</u> is the most precise and <u>least expensive</u> manufacturing environment.

Definition of Monolithic Instruments

- <u>Monolithic instruments</u> are miniaturized systems, combining conventional <u>integrated circuits</u> with novel solid-state components, <u>that interact with their physical environment</u>.

- Concept- Incorporate several instrumentation system functions onto a single die.
  - Transducer/actuator
  - Driver (analog function)
  - Analog/Digital interface
  - Signal processing
  - Data analysis
  - I/O

Classes of Monolithic Instruments

- **Pre-integrated circuit.**
- **During integrated circuit fabrication.**
- **Post-integrated circuit fabrication.**

Adapted from: H. Balthes, and O. Brand, Proceedings of 14th Eurosensors XIV, p1 (2000).

Monolithic Instrument Examples

- Some types of monolithic instruments that have been fabricated include:
  - a-Si:H photodiode arrays.
  - Organic LED micro-arrays.
  - Digital Micromirror Devices.
  - Liquid-crystal microdisplays.
  - Bio-assay array systems.
  - Inter-cellular communications.
- Components proposed for future monolithic instruments include:
  - Thin-film bulk acoustic resonators.
  - Photonic crystals.
  - Planar light-guide systems
  - Group IV-based LEDs.
  - SQUID magnetometers

Fabricated Monolithic Instruments

- **Inkjet heads (Hewlett-Packard, Loveland and Corvallis).**
- **Digital micromirror displays (Texas Instruments).**
- **DNA microarray detectors (Infineon).**
- **Direct neuron communicators (Infineon).**
- **a-Si:H photodiode arrays (Agilent).**
- **Organic LED microdisplays (Agilent, e-magin).**

Texas Instrument's DLP
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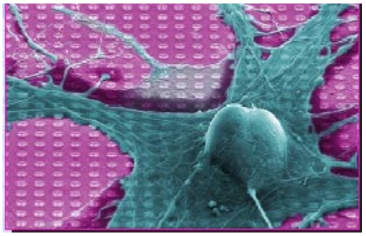
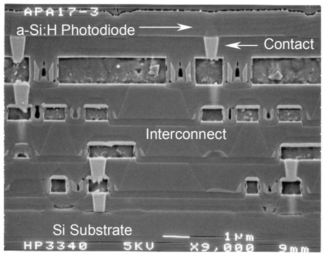
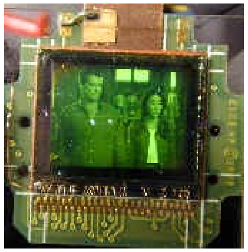


Neuron Communications
© Infineon 2003



a-Si:H Photodiode array
(Agilent Technologies)



SXGA OLED microdisplay.
Agilent Technologies

Advantages of Monolithic Instruments

- **Better performance.**
  - **Improved signal integrity.**
  - **Access to novel transducer technology.**
- **Smaller.**
- **Cheaper.**

What we have come to expect from improvements in integrated circuit technology can be applied to instrumentation systems.

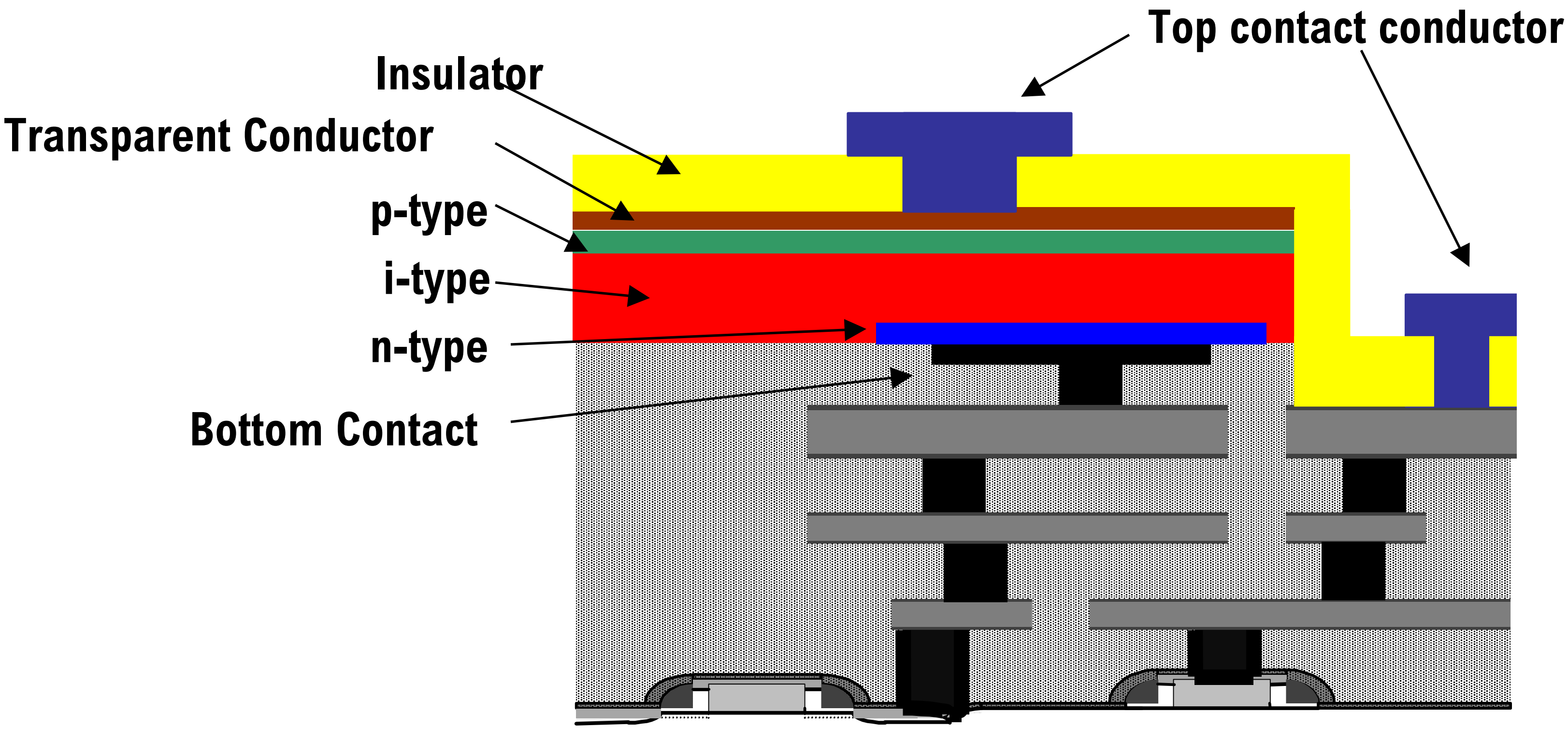
Monolithic Instrument Technologies

- **Elevated Photodiode Arrays.**
- **OLED Microdisplays.**
- **Digital Micromirror Arrays.**

a-Si:H Elevated Photodiodes

- **Hydrogenated amorphous silicon is a deposited semiconductor.**
  - **Bandgap ~1.8 eV.**
- **Advantages**
  - **Higher QE.**
  - **Tunable spectral response.**
  - **Lower thermal effects.**
  - **Higher fill factor.**
  - **Cheaper imager.**
- **Disadvantage**
  - **Subject to metastabilities that can affect performance (Staebler_Wronski Effect).**

Dielectric Isolation Interconnect



- Two extra masking levels.
- Requires a dry etch with high selectivity between two conductive materials.

TFT-Based Monolithic Interconnections

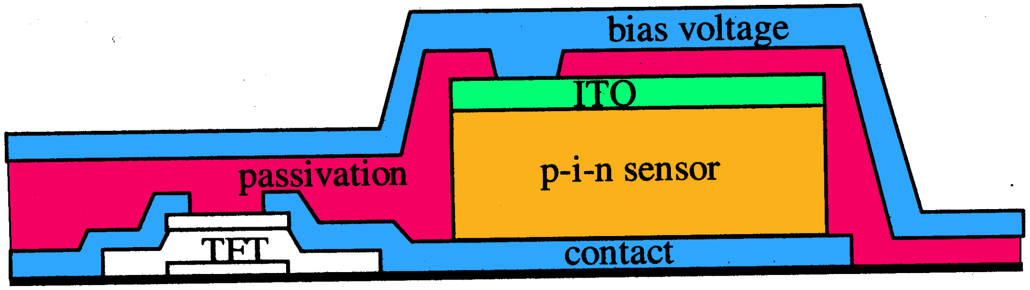


Fig. 4.12. Cross-sectional view of a pixel showing the a-Si:H TFT and p-i-n photodiode sensor

R. A. Street (ed.), Technology and Applications of Amorphous Silicon. Springer, p 162 (2000).

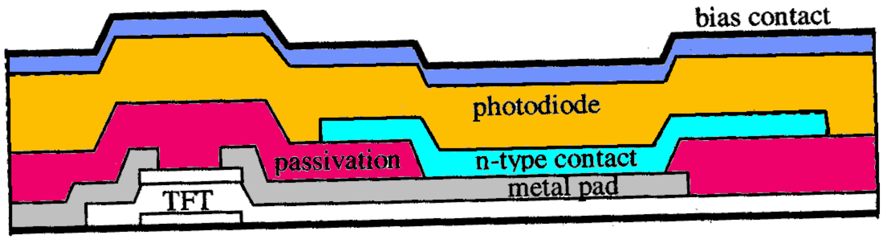
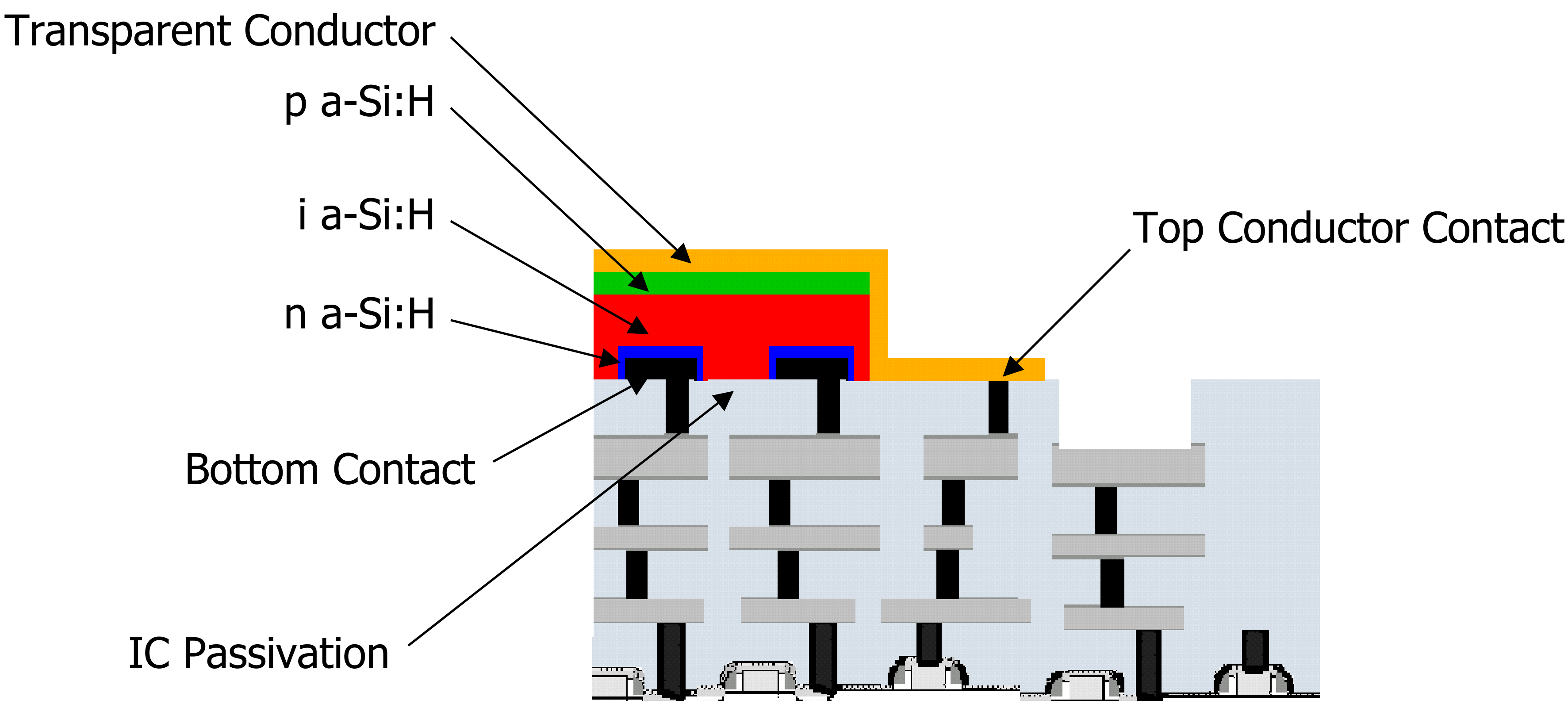


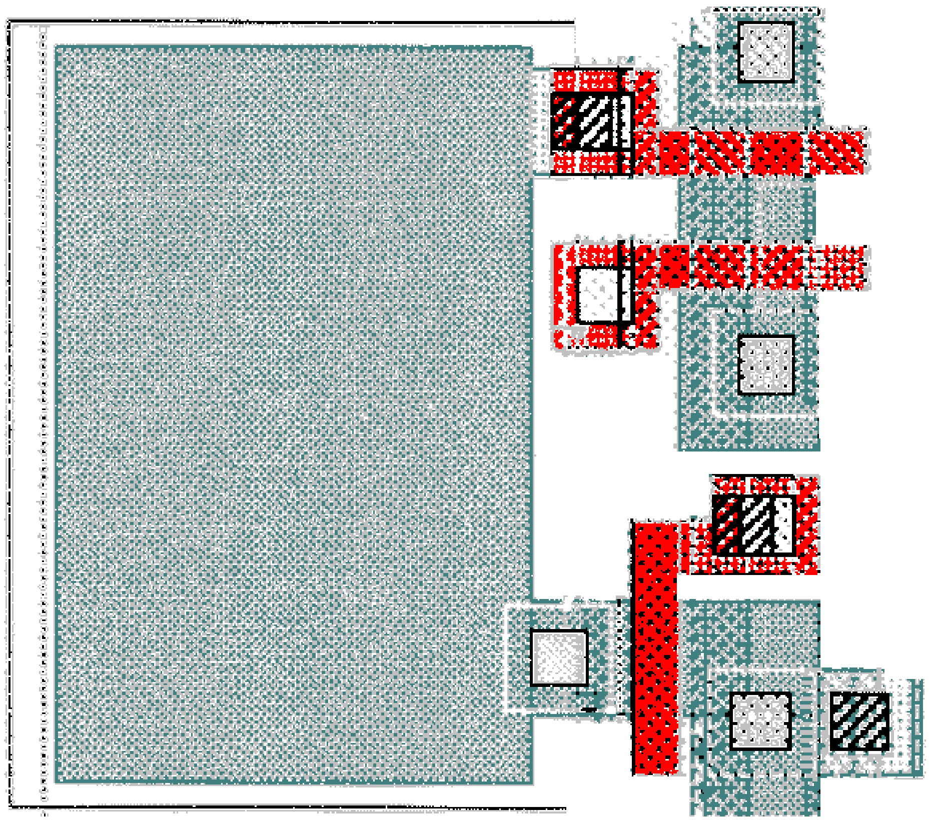
Fig. 4.19. Example of the design of a high fill factor sensor array using a continuous a-Si:H photodiode layer with a patterned n-type doped contact

Local-via Monolithic Interconnect Structure

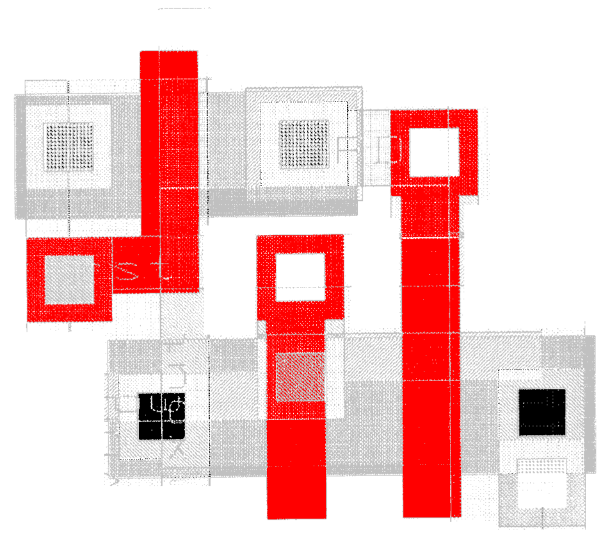


US Patent 6018187

Elevated a-Si:H Photodiodes- Pixel Size Reduction



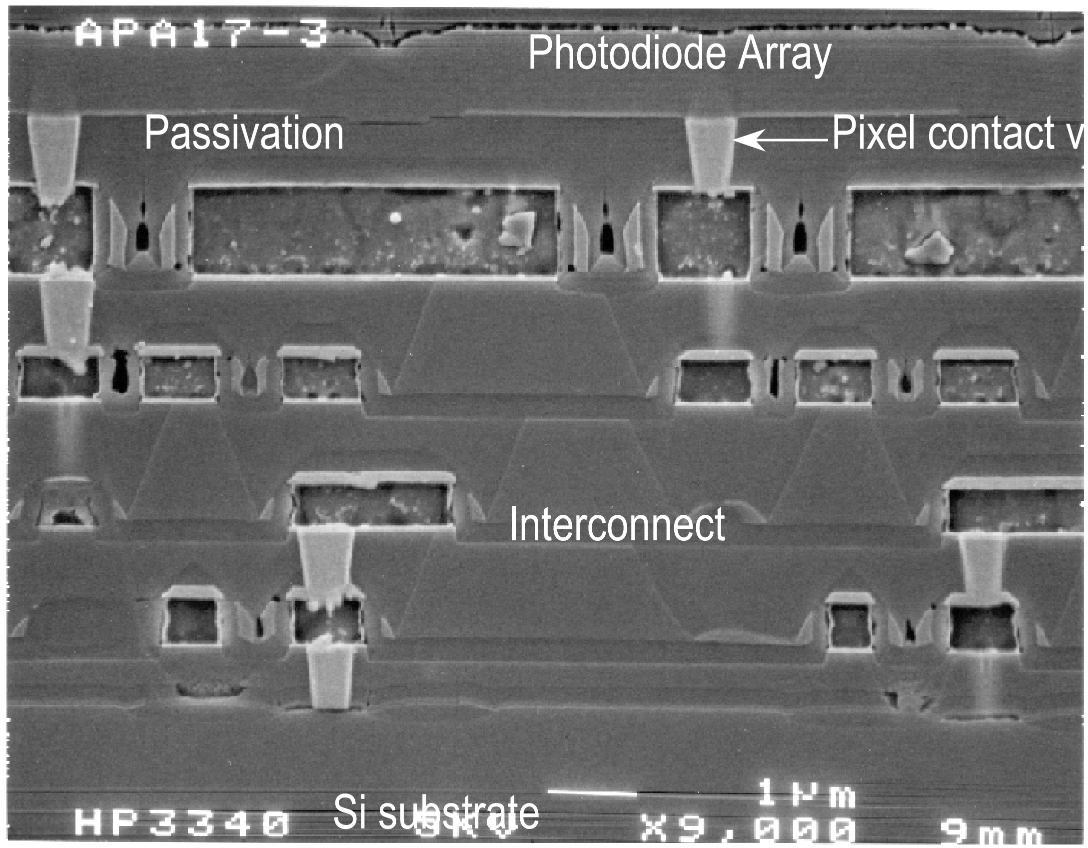
c-Si 3T Pixel



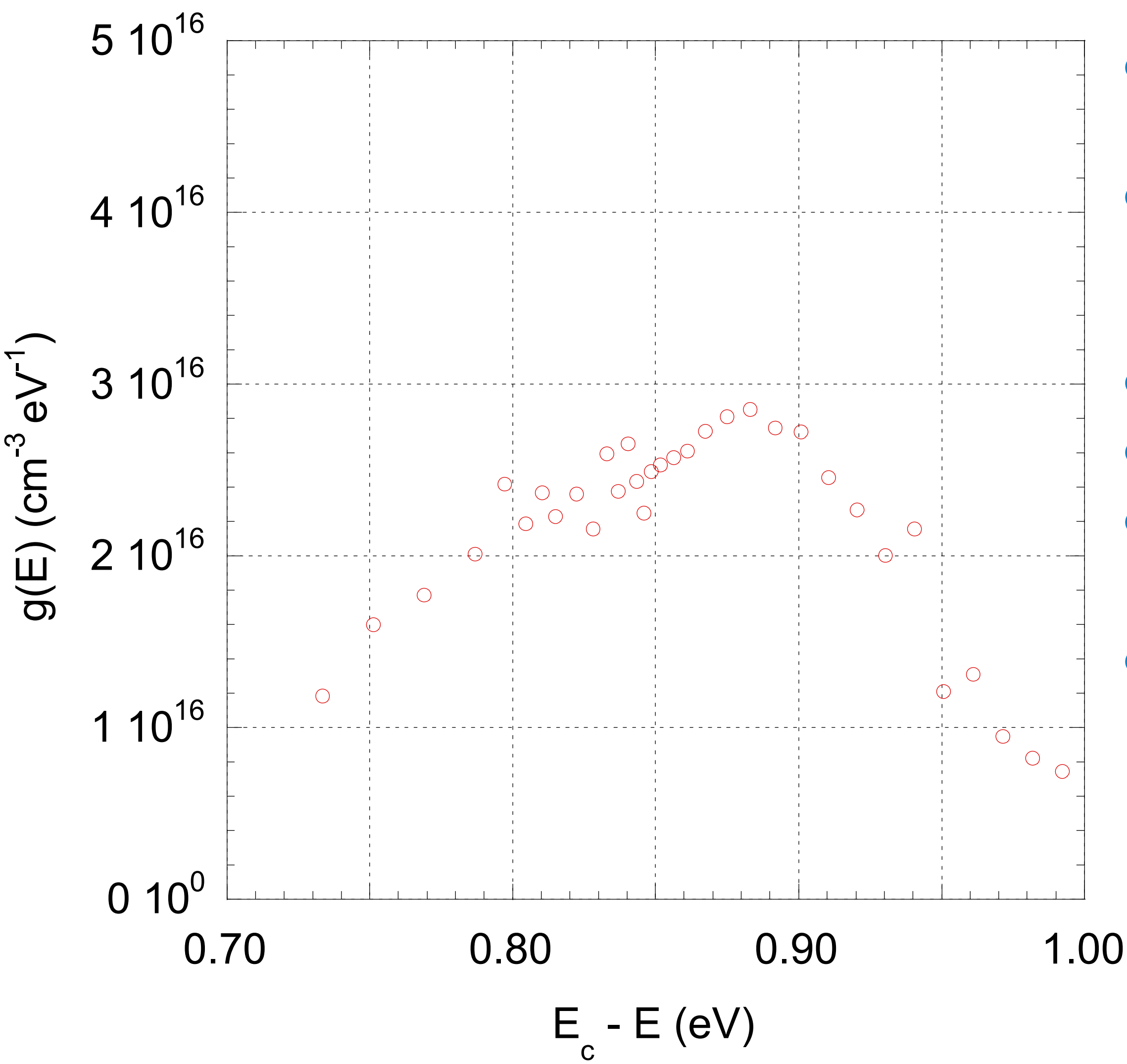
a-Si:H 3T Pixel

Integrated a-Si:H Photodiode/CMOS Stack

- 0.35 μm 4LM CMOS process.
- 5.9 μm square pixel, on a 7 μm pitch.
- Interpixel isolation created by etching of the n-layer a-Si:H.
- Planarized passivation layer.



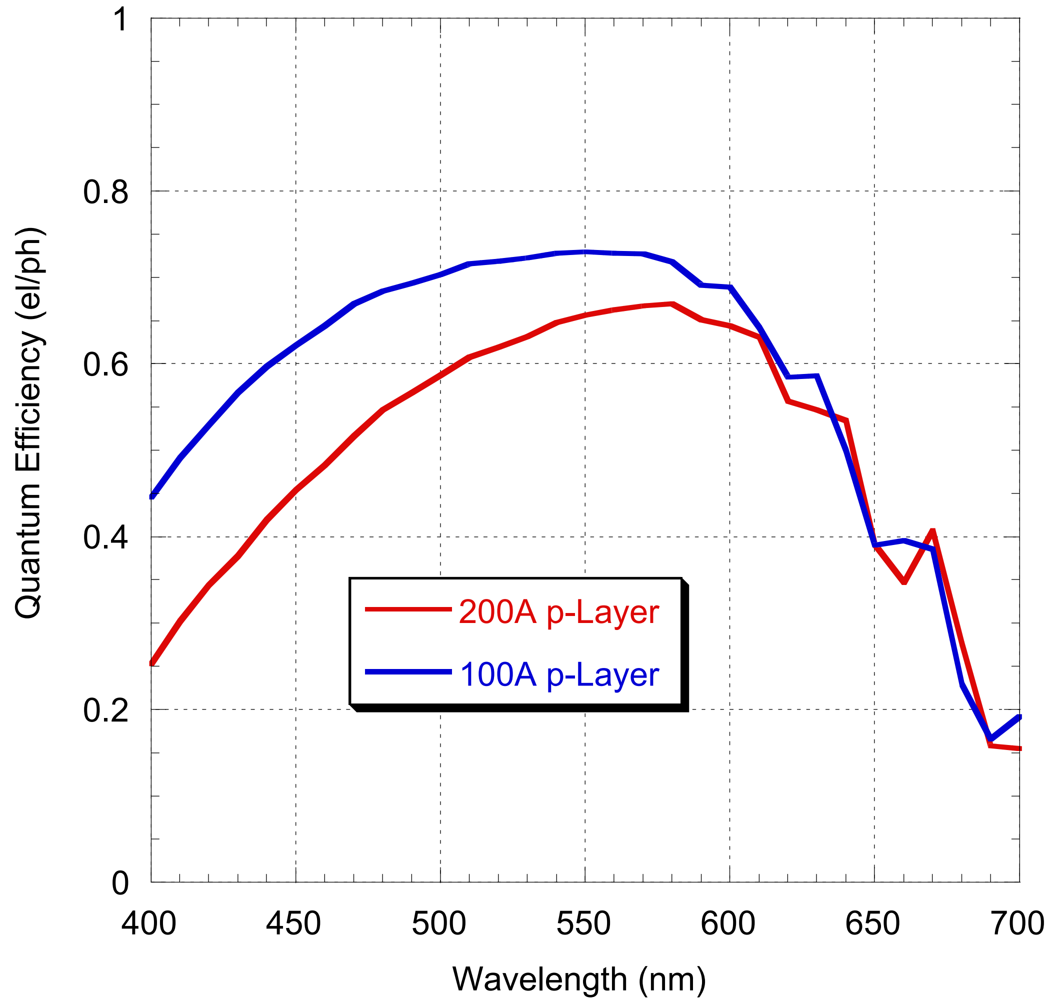
a-Si:H Material Properties



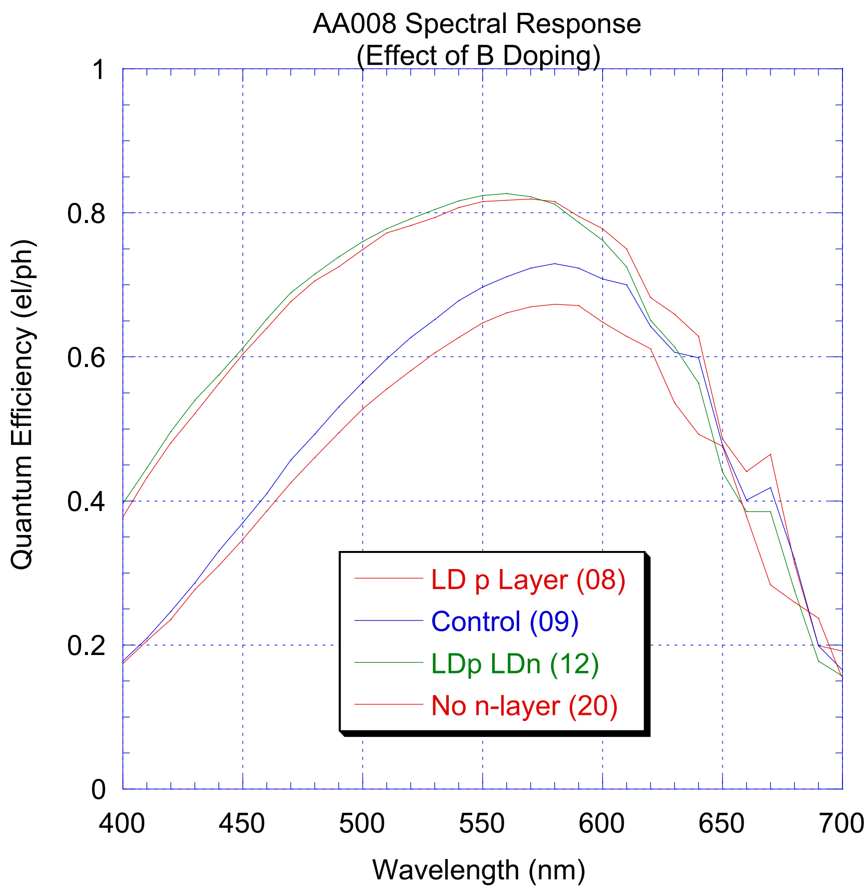
- **Integrated DOS ~2.5 - 4 x 10^{15} cm^{-3}.**
- **Mid-gap peak ~ 0.88 eV from the conduction band edge.**
  - **A second peak at ~ 0.83 eV.**
- **1.85 eV band-gap.**
- **E_a ~ 0.9 eV.**
- **E_U ~ 56 meV.**
- **Deposition Rate > 30Å/s.**

J. Theil, D. Lefforge, G. Kooi, M. Cao, G. Ray,
18th ICAMS Proc., J. Non-crystalline Solids, in press, 2000.

Effect of p-layer thickness on quantum efficiency



Effect of layer doping on quantum efficiency

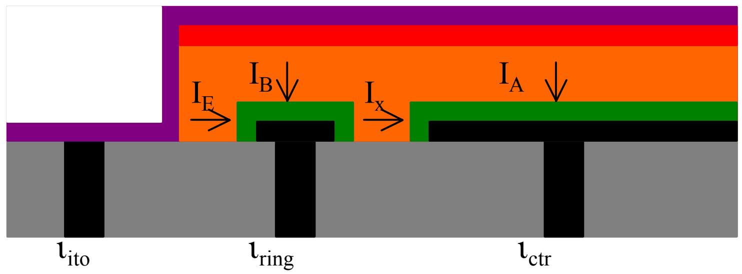


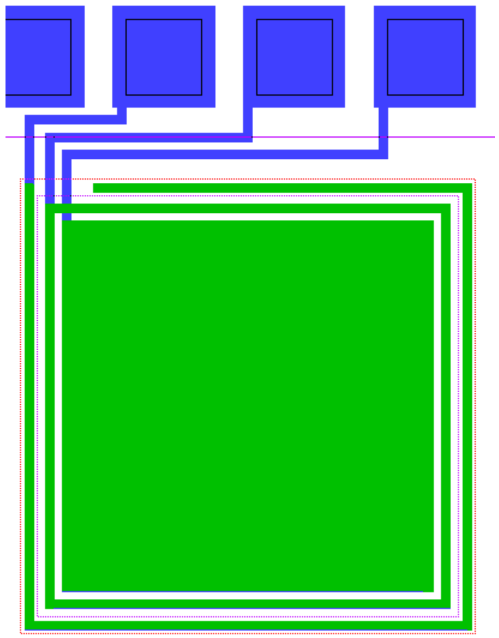
Dark Current Components

- Two components of dark current:
  - Junction leakage.
  - Array edge leakage.

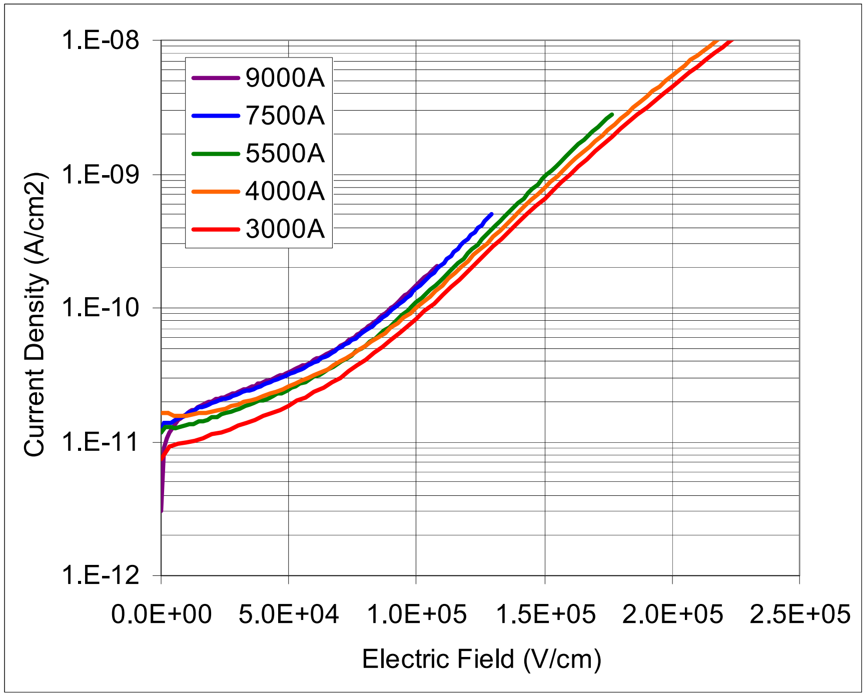
- Guard ring prevents edge current from reaching the array.

- Sweep guard ring and area diode together.
  - Assume: Ix = 0.
  - IE = IA A_{ring}/A_{area} diode.



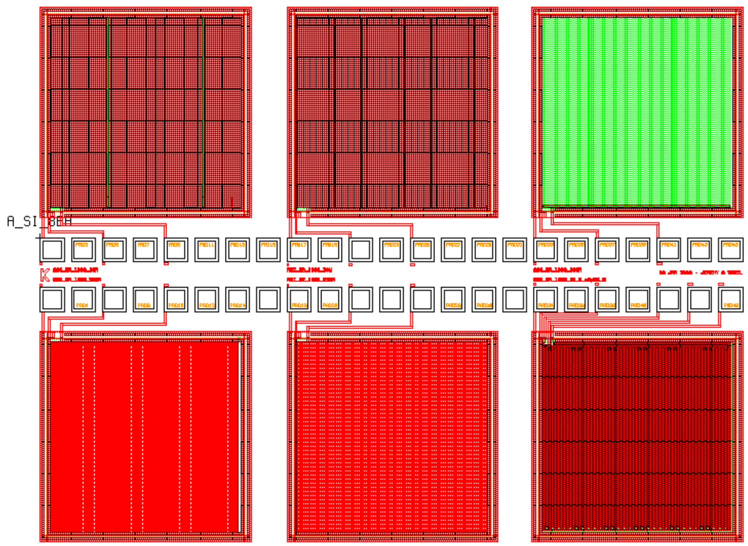


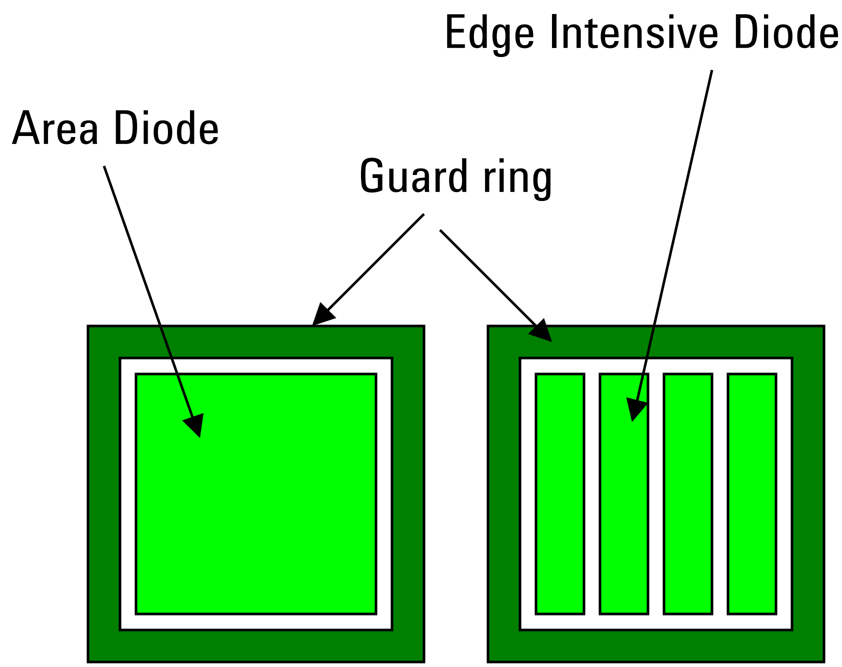
Dark Current Density vs Electric Field



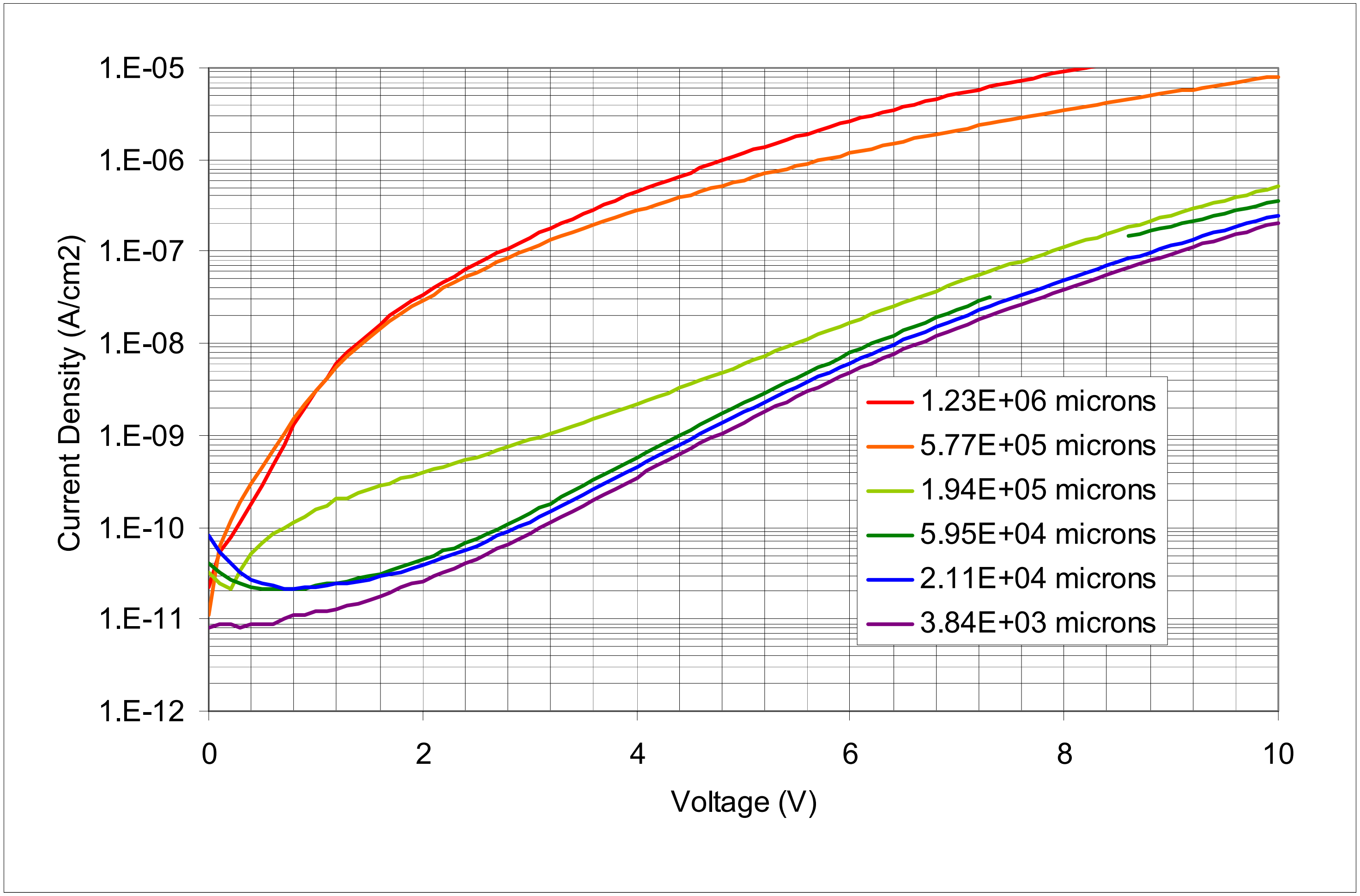
Structures and Junction Parameters

- n-layer thickness: 500Å. ([P] 2 x 1020 cm-3)
- i-layer thickness: 3000 to 9000Å. (5500Å default value)
- p-layer thickness: 200Å. ([B] 7 x 1019 cm-3)

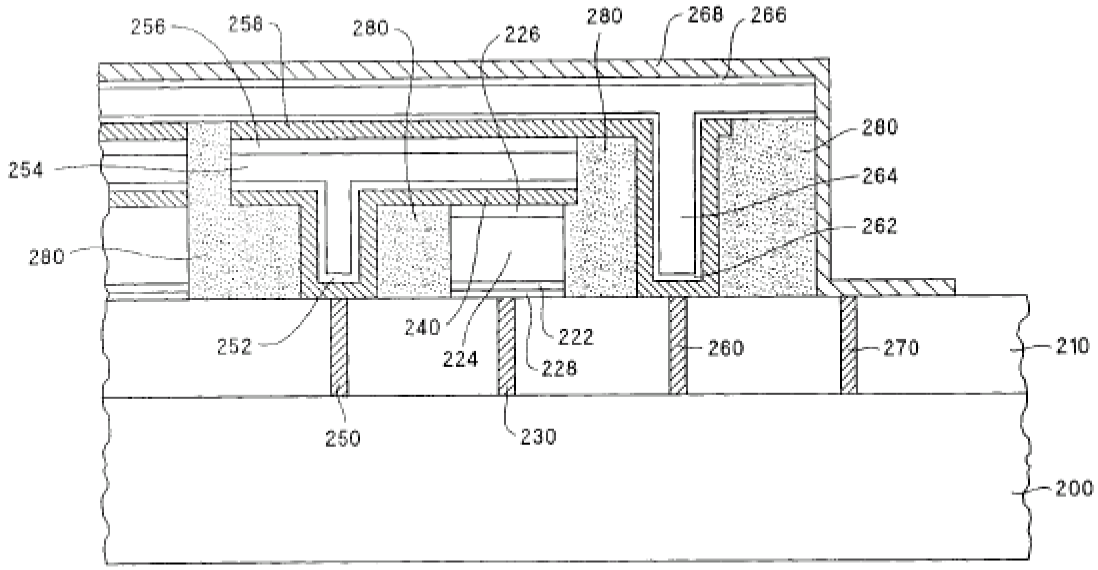




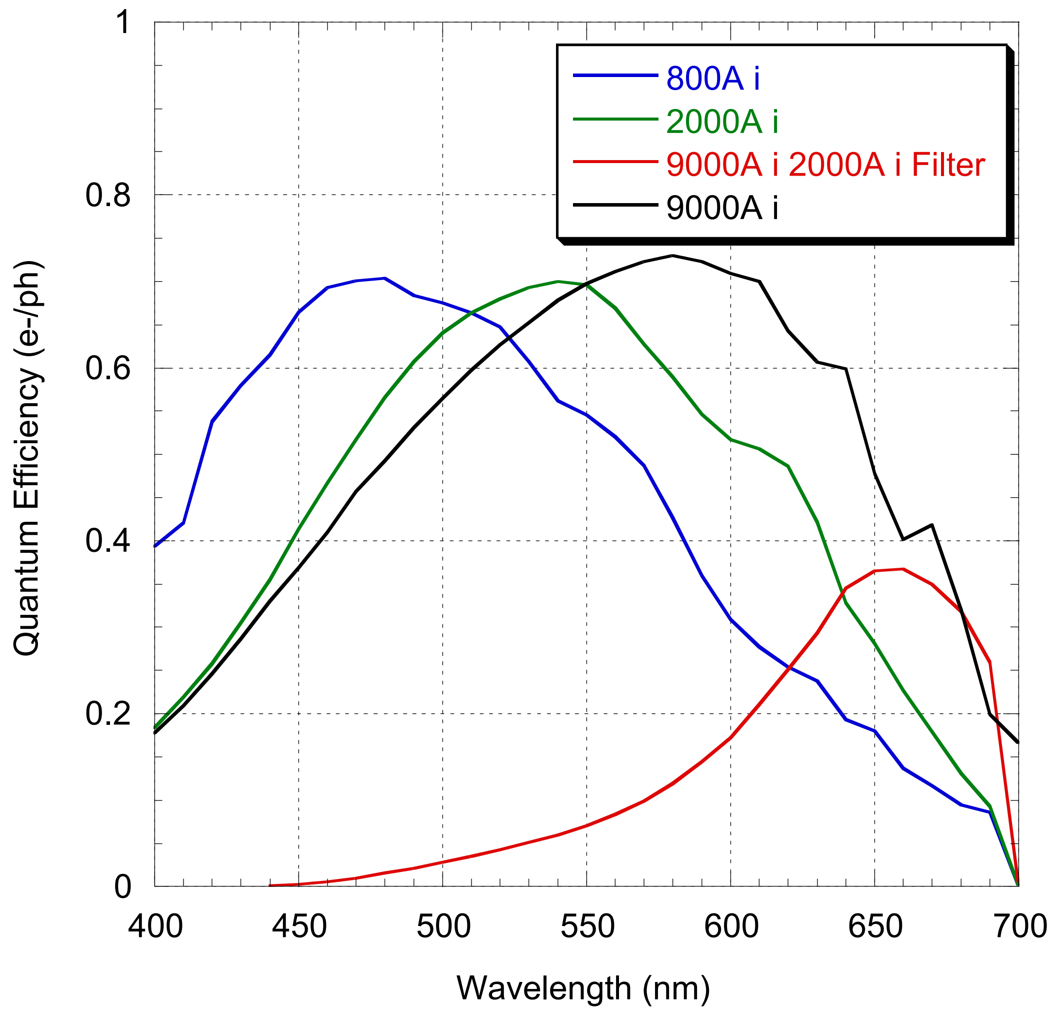
Effect of Pixel Edge Length on Reverse Bias Current (3000Å I-layer)



Stacked Elevated Photodiode Concept



Optical Response of Stacked Diode Elements



a-Si:H Color Sensor Image

(640x480 4.9 x 4.9 μm pixel, 1900 lux)

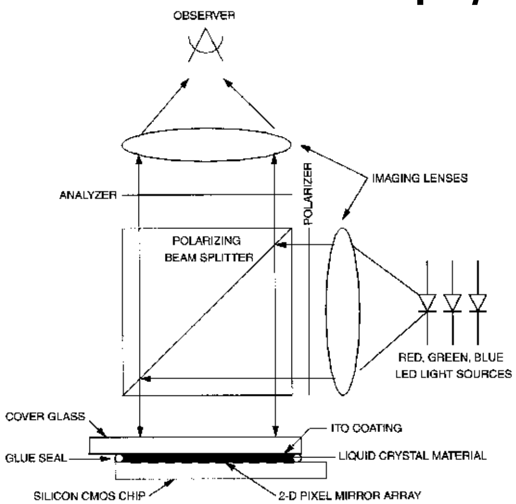
OLED Microdisplays

- Organic Light-Emitting Devices (OLEDs)
  - Charge transport mechanism: localized state-based hopping.
  - Use for large area emissive displays, fabricated using evaporation or printing.
  - Just gaining acceptance.
  - Has lifetime issues.
- Applications
  - Eyepiece imagers (digital cameras).
  - Eyeglass displays.
    - Computers
    - Instrumentation
- Advantages over LCD microdisplays
  - Smaller
  - Brighter (more power efficient).
  - Less expensive (fewer components required).

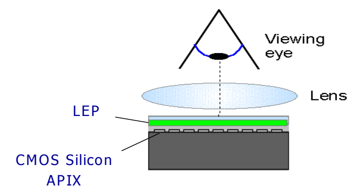
Thanks to Howard Abraham for driving the Ft.Collins Development

Microdisplay Systems

LCD/LED-based Microdisplays



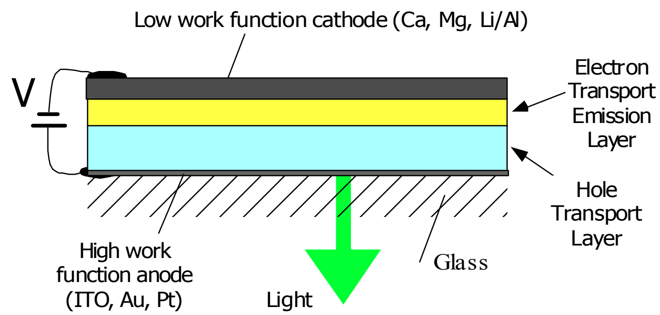
Microdisplay Based on
Light Emitting Polymers



Value Proposition:
Simpler, Cheaper, Brighter

Organic LED Materials

Organic LED's: Materials and Devices



OLEDs rely on organic materials (polymers and small molecules) that give off light when tweaked with an electrical current

Small Molecules (vacuum evaporated)

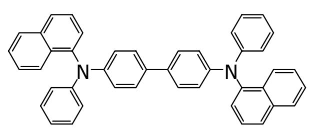
HTL: metal-phthalocyanines, arylamines (CuPc, NPD)
ETL, EML: metal chelates, distyrylbenzenes

Eastman Kodak, Pioneer, Idemitsu Kosan, Sanyo, FED Corp., TDK

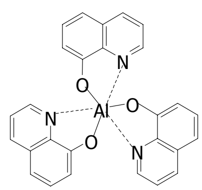
Polymers (spin cast)

HTL: conducing polymers (PDOT, PANI)
ETL, EML: polyphenylenevinylenes, fluorenes

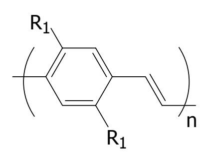
CDT, Philips, Uniax, Dow Chemical, DuPont



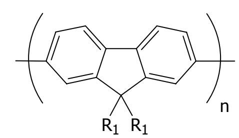
NPD (HTL)



Alq_3 (ETL, EML)



R-PPV (EML)



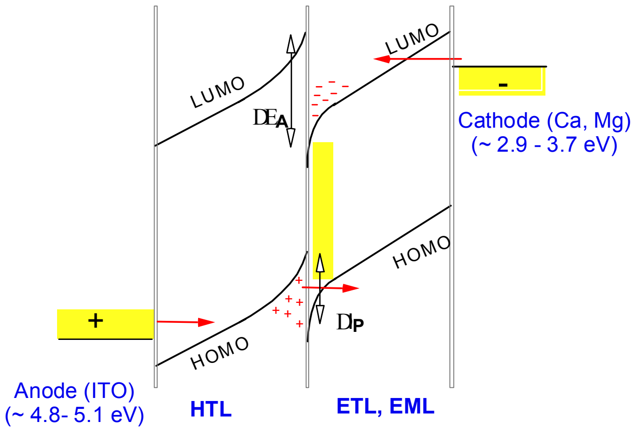
Polyfluorene (EML)

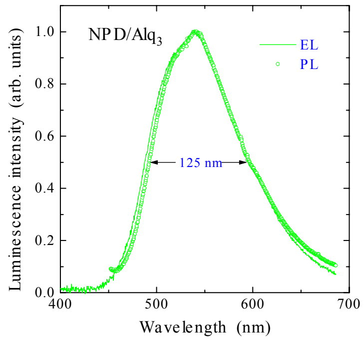
Operating voltage ~10V

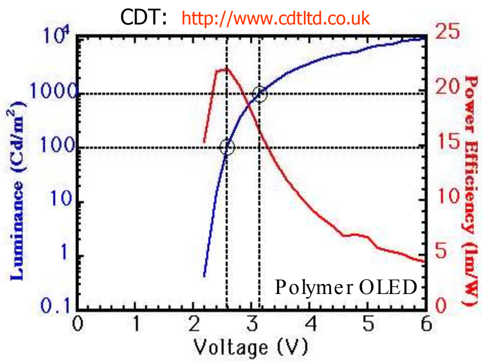
Operating voltage ~5V

Organic Electroluminescence

Organic electroluminescence by charge injection







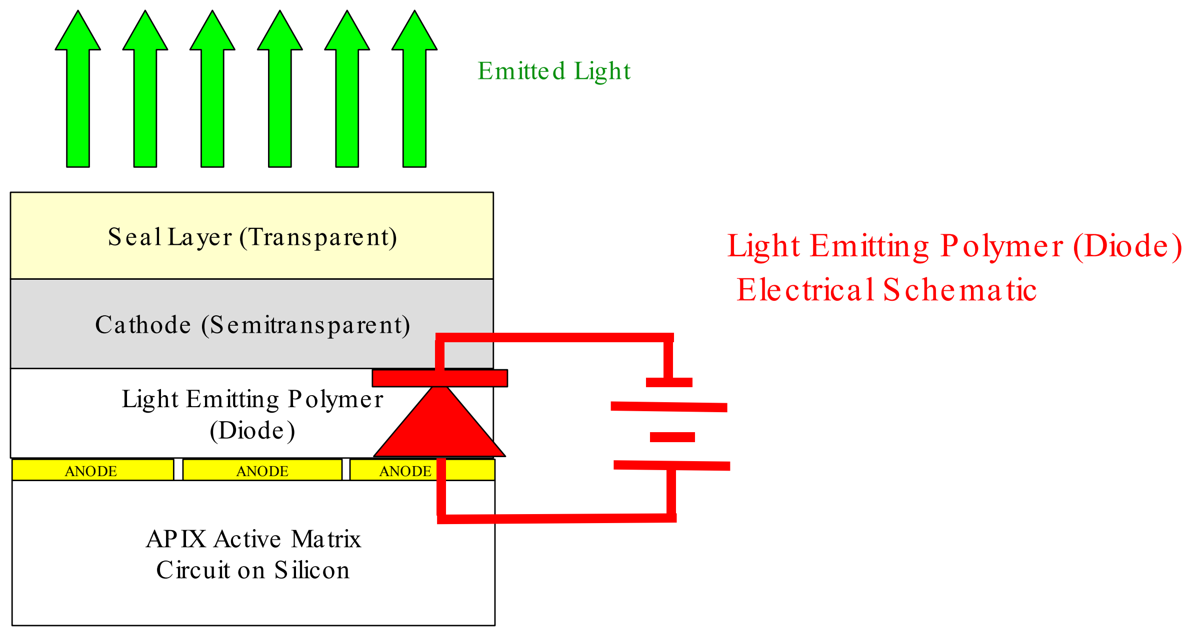
- Hole injection from high work function transparent anode (ITO) and transport through HTL
- Electron injection from low work function cathode (Ca, Mg, LiF/Al, CsF/Al) and transport through ETL
- Since $I_P < E_A$ electrons are blocked by HTL and holes tunnel to ETL
- Formation of excitons and light emission from ETL

- Diode-like I-V (no light on reverse bias)
- Low turn-on voltage (~ 2 V)
- Operating voltage >> turn-on voltage
  - Charge Injection limitations
  - Charge Transport limitations
- Efficiency
  - 1-5% ph/el
  - 1-22 lm/W

OLED Diode Construction

Process Overview for APIX/LEP Microdisplay

Device Layout:



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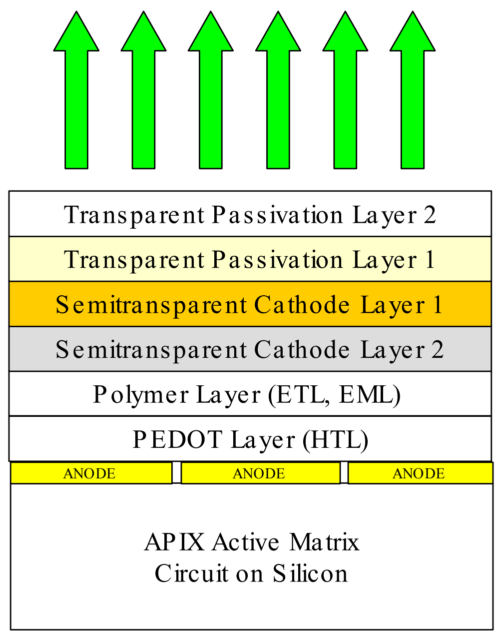
OLED Challenges

- **Environmental sensitivity.**
- **Device lifetime.**

OLED Diode Structure

Process Overview for APIX/LEP Microdisplay

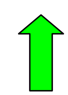
Device Layout:



Specific Fabrication Steps (sequence is bottom up):

- Functional test, Mount chips to daughter board, Wire bond pads to board, Final test
- Encapsulate cathode with seal process steps. N2 atmosphere.
- Thermally evaporate semitransparent cathode using die-sized shadow mask. N_2 atmosphere.
- Spin Electron Transport Layer (also the Emission Layer) light emitting polymer. N_2 atmosphere.
- Bake PEDOT (180ºC, 1 hr).
- Spin Hole Transport Layer (PEDOT).
- Surface clean (IPA/O_2 Plasma).
- Final metallization optimized for anode and bonding pads. Anodes form reflective pixels. Functional test.

Process APIX on 6" or 8" silicon wafers.



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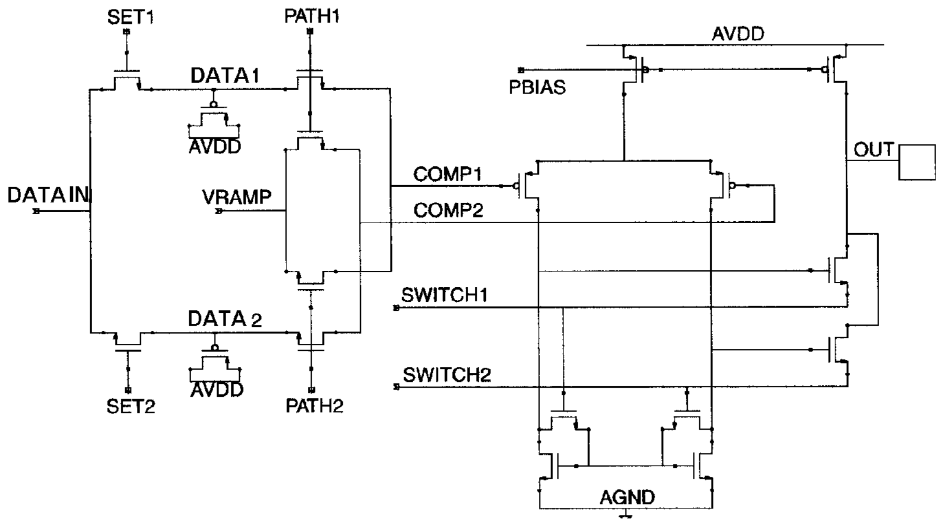
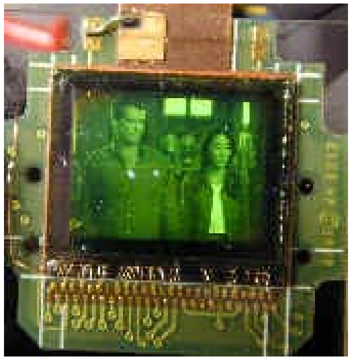
OLED Microdisplay Driver Circuits



Pulse-width modulation pixel driver circuit.

OLED Microdisplay Operation



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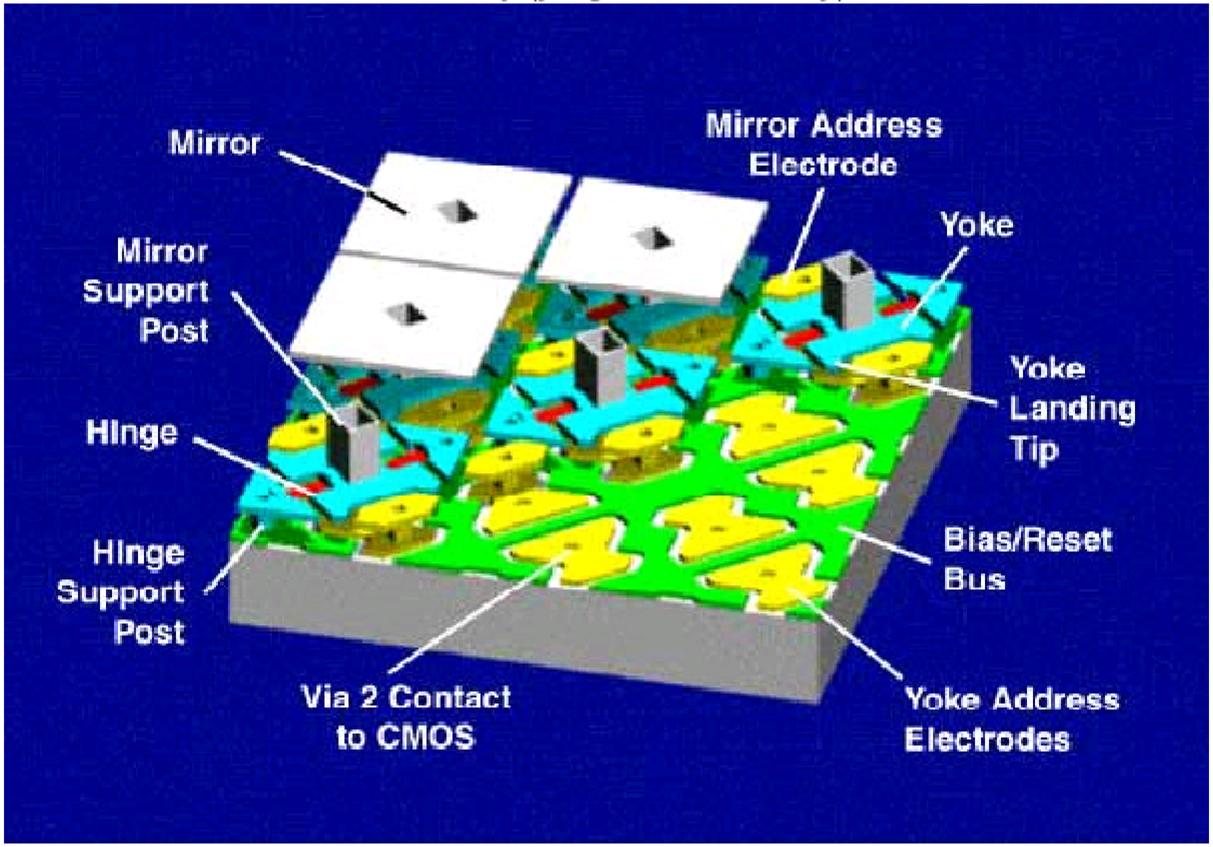
Digital Micromirrors

- **Invented at Texas Instruments in 1987 (by Larry Hornbeck).**
- **Build hinged mirrors from BEOL metallization over SRAM pixels.**
- **Operates by electrostatic attraction between mirror and pixel electrodes.**

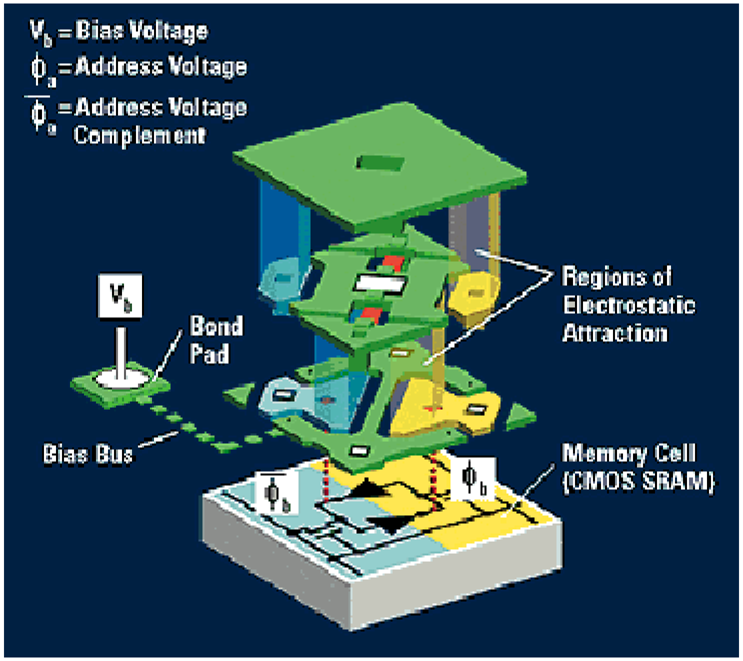
Digital Micromirror- Construction

DMD array (progressive cutaway)



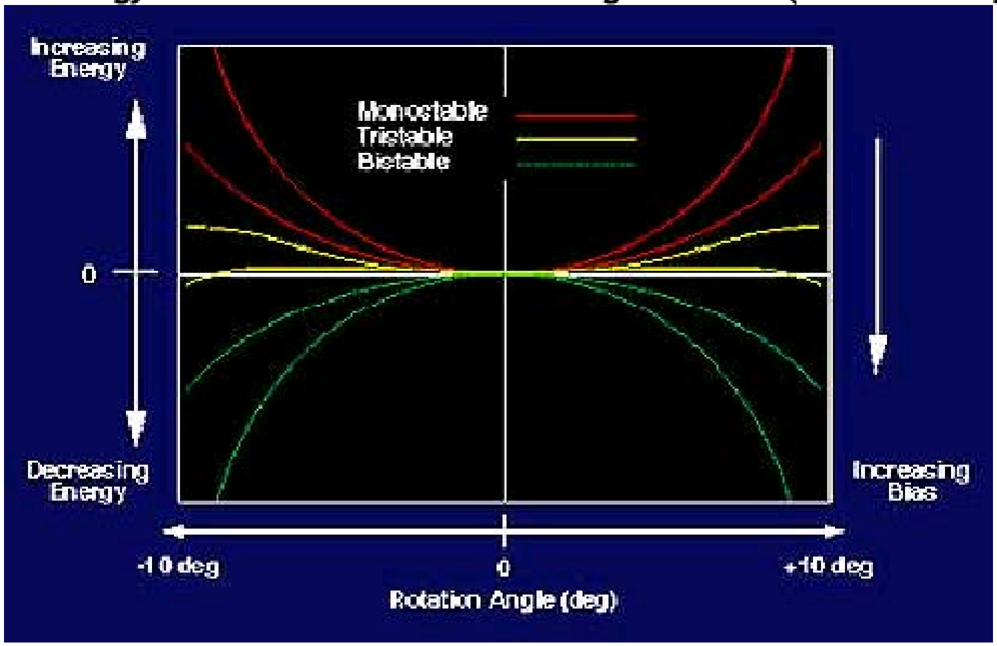
Digital Micromirror- Schematic

DMD Pixel Electrical Schematic



Digital Micromirror- Mechanics

Potential Energy of a Mirror as a Function of Angle and Bias (address voltage = 0)



Digital Micromirror- Applications

- Projections Displays
- Digital Movie Projectors
- Digital Printing and Photofinishing
- 3D Non-holographic displays
- Maskless photolithography
  - DNA sequencing
- Broadband switching
- Holographic storage
- ... Anywhere LCD can be used, with higher contrast.

http://www.dlp.com/dlp_technology/images/dynamic/white_papers/152_NewApps_paper_copyright.pdf

Integration Challenges

- Known Issues
  - Material compatibility with the "nominal" process flow.
    - Adverse effects of the standard structures.
    - Adverse effects of the new structures.
  - Manufacturability of new unit modules.
  - Materials optimization.
    - Material performance considerations.
    - Integration compatibility considerations.
- Unknown Issues
  - There will be plenty of them.
  - We encountered 8 major issues in one project.
    - Example: The 9 causes of adhesion failure.

Expect the unknown!

The Future

- Integrated circuit manufacturing platforms can be extended to make monolithic instruments.
- Many classes of monolithic instruments can be created.
- The attributes of monolithic instruments enable hundreds of new applications.
  - Low cost
  - Small size

- There are plenty of opportunities out there.
- Who is going to take advantage of them?