What Camera Manufacturers Want

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***Abstract*—Rapid advances in CMOS image sensors and SOCs, (which include image processing) are currently taking place. To date these advances have enabled the rapid proliferation of cameras in mobile phones and other consumer electronic devices. This paper takes the viewpoint of the camera manufacturer and describes what further advances are most needed to reduce the cost, size and to further improve the quality, performance, and yield of camera modules.**

I. Introduction

Camera module annual shipments grew from ~20Mu in 2002 to >550Mu in 2006 and is one of the fastest growing products in digital imaging. Module production is pushing many technical and process boundaries. This article briefly discusses the market for camera modules, and focuses on the cutting edge technical issues and developments in module construction and assembly, imager die layout, pixels trends, image processing, calibration, test, singulation, sawing and transport.

II. Camera Markets

What camera module manufacturers want is fundamentally driven by end-market and end-user requirements. A fixed focus camera module must be able to take a sharp self-portrait at 20-30cm while also having acceptable sharpness of distant objects, for example.

The primary requirements for mobile phone cameras are acceptable image quality, low-price and small physical size. The mobile handset market can be divided into four segments as shown in Figure 1. In order to access the volumes in each mobile phone market segment the required price points must first be met. The best solution that meets the price point tends to obtain the highest volume. Substantial technology developments are required to increase performance and drive down costs at a compound rate >15%/yr as shown in Figure 1. From 2002 – 2007 increased resolution and lower camera prices were driven primarily by pixel geometry shrinks from 5μm to 1.75μm. Additional technologies like chip-scale packaging and innovative new, low-cost optics are required to be high-volume production ready in the next year to sustain these cost reductions and further expand the camera module market.

III. Camera Module Construction and Assembly

Market demand for ever-smaller camera modules requires that manufacturers utilize the latest in packing and assembly technologies. A block diagram of a typical camera module is shown in Figure 2. VGA resolution camera modules today can be smaller than 5mm x 5mm x 3mm.

Figure 3 shows a sampling of difference camera module designs.

Camera modules use a wide range of assembly technologies. Imager die can be mounted using COB, flip-chip, or chip-scale packages. Die may be mounted on fiberglass or ceramic substrates, or serve as the substrate itself. The lens and IR filter are typically assembled as a subassembly and mounted to the substrate with a plastic housing. During assembly, components may be passively or actively optically aligned. The module can be attached to the handset using either a flexible PCB or board-to-board connector, or the module may be mounted in a socket.

Figure 4 shows the cross-section of a common module design. The bare die imager is epoxied and wire bonded to a fiberglass PCB substrate. The lens/IR filter barrel is mounted to the substrate by a plastic housing. This type of design is rapidly being replaced by more streamlined designs, involving fewer components and assembly steps.

IV. Imager Die Layout Considerations

With few exceptions, camera modules (1) are square in footprint, and (2) have the optical center coincident with the mechanical center. Customers and yield management also prefer everything fit within the housing; protrusions where parts can break off are unwelcome. These requirements place important constraints on the imager die layout.

While the center of the die may intuitively seem like the best place for the center of the pixel array, that is only true when the die is the only component on the substrate top surface. In most real-world applications, the module design includes a variety of passive components. To fit wire bonding pads and these passive components under the housing, the imager die must be shifted from the mechanical center, shifting the pixel array center as well. The ideal amount and direction of shift depends greatly on the module design and assembly processes. Imager vendors must work closely with camera manufacturers to ensure the die layouts permit designs that meet customer requirements.

Figure 5 shows how die layout affects module size. A poorly placed pixel area forces the module to be much larger necessary. By intelligently offsetting the pixel array the module can be much smaller. There is even room for passives without affecting module size.

V. Pixels

Smaller pixels make for smaller, more cost-effective die, with 1.75μm pixels currently representing the state of the art. As pixel sizes decrease, optical design challenges increase and lens yields decrease. Because the sensor die still represents the majority of the cost of most modules, shrinking the sensor die by reducing the pixel size reduces the overall module cost. At some threshold, however, smaller pixels will increase, rather than decrease, module cost. Figure 6 shows how as pixels shrink, the cost of building a module is dominated by lens cost and manufacturing processes rather than die cost. Smaller pixels are also less sensitive to light and noisier, degrading image quality. Smaller pixels are definitely possible, but it's not clear that they're desirable.

Smaller pixels also complicates the guiding of light to the photodiode, requiring the lens system and die-level optics be better matched. Lens/sensor mismatch can cause pixel noise and chroma nonuniformity in the image corners due to excessive shading correction and sharpness, and focus failures in the center. Since changing the die's optics is faster than changing a lens design, sensor vendors must be willing to tune their optics to match a given lens, rather than the other way round. This may create some inventory management issues, but the alternative is a poorly matched optical system and inferior image quality.

VI. Image Processing

Image processing in camera modules for cell phone applications has been primarily used to correct for lens shading issues and to enhance color performance. The sensor manufacturers have also leveraged it to obscure defective pixels and fixed pattern noise in their products for yield enhancement in the wafer fab. While auto-correction features like auto-white balancing and auto-gain correction ensure that the camera modules are user friendly. However, still the amount of image post processing in cell phone applications has been quite minimal compared to the digital still camera and digital video camera market.

A key area for improvement is compensation for the performance of smaller pixels. Better noise reduction, smarter demosaicking, and improved sharpening algorithms are crucial to reducing color crosstalk, temporal noise, and fixed pattern noise. If the noise of smaller pixels can be managed, low light performance can be maintained without other image quality tradeoffs, like desaturating color or increasing lens f-number.

Bad pixel correction must be able to correct for cluster defects, not just single pixel failures. As will be discussed later, contamination of the imager surface is the largest cause of module defects. Pixel sizes decrease through the use of new manufacturing processes, but dust and other particles stay the same size. The ability to correct bad pixel clusters will reduce module costs both through increased yields and reducing the need to build more expensive or larger clean room facilities.

Better lens shading correction algorithms are needed as well. Lens vignetting correction is called on to undo lens vignetting, lens alignment error, and pixel array nonuniformities in color and photoresponse. Common assumptions like uniform response across color channels, perfect alignment of the lens to the pixel array, and polynomial lens shading functions all need rethinking. New algorithms must correct each channel individually using arbitrary sized grids of control points. Lens correction also must vary with illuminant, since color shading varies with illuminant (daylight, tungsten, fluorescent). Go away, pink centers and blue corners.

Support for the many forms of optoelectromechanical systems, like auto-focus and optical zoom, is also critical. Image processing must offer both custom algorithms and provide a complete, robust solution. Even better, any image processing that eliminates the need for moving parts. Moving parts are expensive to assemble, create particles through friction, and are unreliable. Innovations like extended-depth-of-focus, nontraditional optics, and sophisticated post-processing have the potential to enhance the appeal of fixed focus modules and to allow for more

compact auto-focus and zoom solutions.

Digital still camera features like image stabilization, automatic image judgment, and multiple image capture will migrate over to camera modules.

VII. Camera Calibration

No two camera modules are the same; even within the same production run there will be variations in color response, lens alignment, etc. The industry made significant progress in variation-reducing methods (process control, screening through test), yet typical module performance still falls short of industry demands. The only remaining option is to measure each module's characteristics, and later correct for them, a process generally called calibration.

Calibration has three phases: (1) measuring the performance of each camera module in production, (2) transferring that information to the each handset, and (3) using the information to tune the image processing for optimal image quality. To date, the greatest barrier has been transferring the calibration data to the right handset. The only viable solution is to store calibration data within the camera module itself.

Recently, image sensor suppliers have begun adding nonvolatile memory to their devices. Some include a few bytes, some several kilobytes. An exciting advance, nonvolatile storage will lead to better image quality. But first the industry must decide how to use it. What kind of data is needed for calibration? A good place to start is with the current register set provided to optimize image processing. Module serial number, lens identification, alignment data, color response data (color matrices, or tables), lens shading and sensitivity or linearity data. Calibration data could require a few bytes or many kilobytes, depending on the format and scope.

It's crucial to recognize that having calibration data alone is not enough. The image processing has to be prepared to use it. For example, consider the top view of a camera module shown in Figure 7. The optical center of the camera is represented by a X and is offset from the pixel array center due to lens to SOC misalignment caused by camera assembly. The camera optical center X can be measured during the calibration process and stored in camera memory. To be useful, the camera image processing must use the camera optical center data to adjust the lens shading correction, for example. Another possibility to reduce system costs with shrinking pixels would be to add a few extra rows and columns to systems using 1.4μm pixels. The boundaries of the active pixel array could then be adjusted to compensate for the camera optical center without reduction in resolution.

Very few providers of image processing have clear plans for what calibration data they could use, or in what format. Camera manufacturers can measure many kinds of performance, and record the data in many formats. The industry should openly develop data standards and methods to ease adoption of this key technology.

VIII. Test, Singulation, Sawing and Transport

To optimize yield and quality the camera manufacturers are targeting two areas of improvement of sensor fabrication: surface contamination and test process alignment.

Surface contamination is the single largest source of yield loss in camera manufacturing. Both silicon vendors and camera module assemblers are dedicating enormous effort towards contamination reduction.

The two main sources of contamination are debris from die sawing and clean room processes. Die sawing generates particles, which tend to stick to the organic coatings on the imager surface, as shown in Figure 8. Debris also tends to chip off the edges of the die during handling. Aside from die debris, the surface properties of the die tend to increase contamination.

The organic coatings used for microlenses attract and keep particles through static electricity, van der Waals bonding, and surface tension, reducing the effectiveness of cleaning processes[1]. Glass-on-die technologies aimed to reduce surface contamination, but the loss of economies of scale and unaddressed static charge effects limit the technology's effectiveness. New efforts to reduce static charge generation with conductive coatings are expected to surpass the cost/performance of glass-on-die processes[2]. Sensor vendors are also working to eliminate places for contamination to lodge, through the development of gapless microlenses and non-stick inorganic coatings.

Historically, particles could be acceptably detected by visual inspection under 20x magnification. As pixels shrink to 1.75μm and beyond, visual inspection is impractical due to the throughput and quality requirements. Sensor vendors must use 100% automated inspection to monitor residual contamination after wafer washing.

In addition to surface protection technologies, manufacturing and transportation processes must avoid both surface damage and dust build up in order to minimize the particle-induced yield loss.

Reducing functional die failure rates requires the sensor suppliers to apply existing test equipment more effectively. Wafer level test patterns, algorithms, and test conditions must be aligned with the camera settings used by phone OEM. Camera manufactures and sensor suppliers need to partner to ensure settings on the phone level have been optimized for mass production.

IX. Conclusion

Camera modules are a complex system, involving a myriad of disciplines, technologies, and processes. Advancements in die design, pixels, image processing, calibration, test, and handling are all needed to achieve the next level of quality. Performance is limited by the weakest link, and all areas have to develop together. The sheer size of the market opportunity ensures that the required resources will be invested, making camera modules one of the most exiting products in digital imaging.

References

[1] Ultraclean Surface Processing of Silicon Wafers: Secrets of VLSI Manufacturing, Chapter 6.3: Adhesion forces between a Wafer and a Particle, Takeshi Hattori, 1998 Springer, ISBN 3540616721

[2] Indium Tin Oxide for transparent EMC shielding and Anti-static applications, J. Eite and A. G. Spencer, Diamond Coatings Ltd., Unit 11, Lodge Forge Trading Estate, Cradley Road, Cradley Heath, West Midlands, B64 7RW, UK. www.diamondcoatings.co.uk. Presented at EMCUK 2004, Newbury, UK, 2004.

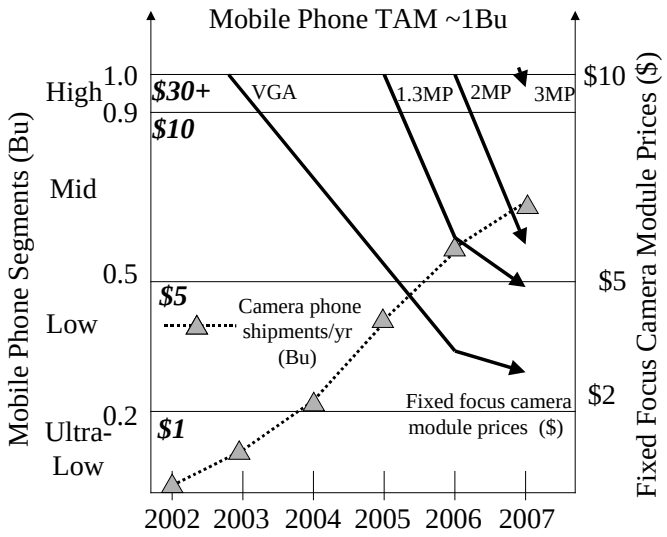

Figure 1. Camera module market size by price and segment.

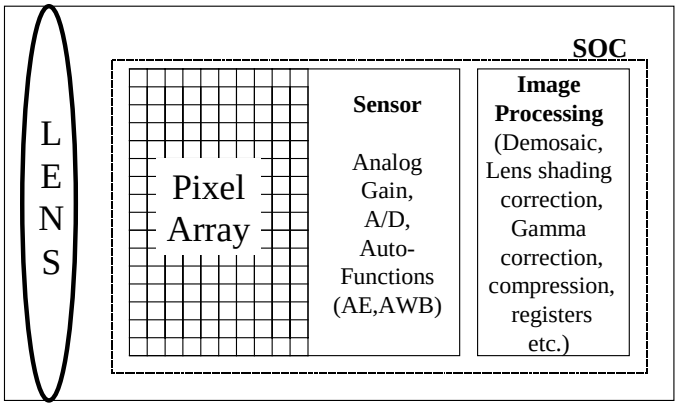

Figure 2. Fixed Focus Camera Module Block Diagram

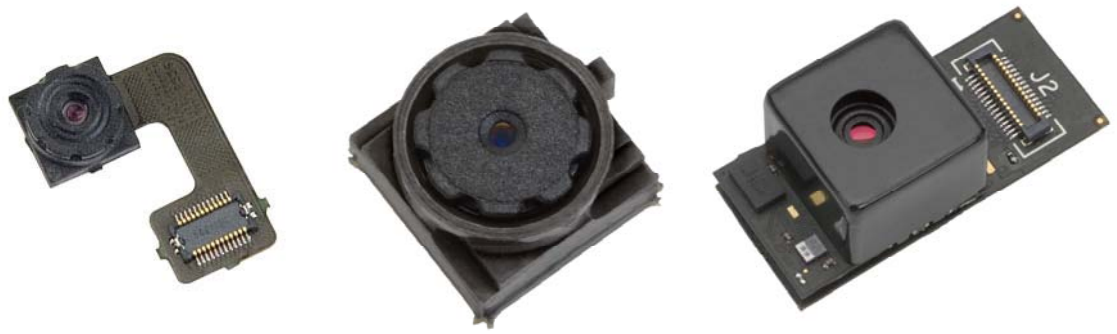

Figure 3. Examples of camera modules. Fixed-focus module with flexible PCB interconnect, left. Fixed focus socketable module, center. Autofocus camera module with calibration memory, right.

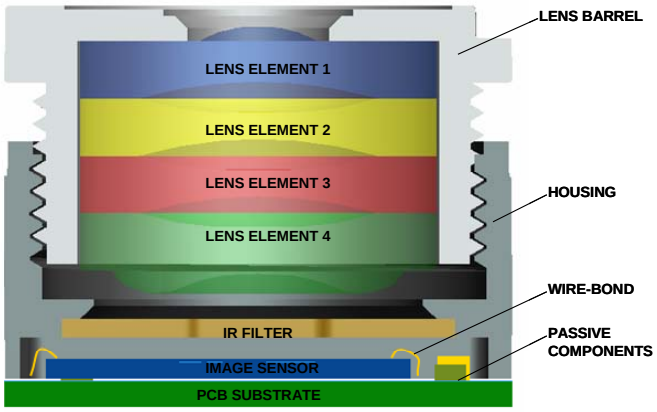

Figure 4. Cross-section of typical camera module.

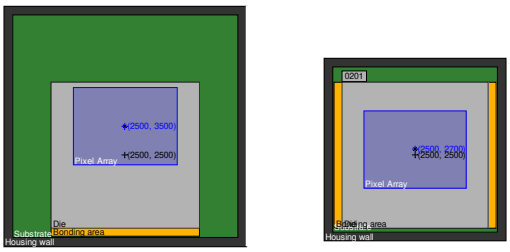

Figure 5. Effect of imager die layout on module size. Poor die layout, left. Good layout on right. Pixel array: blue, die area: gray, bonding area: orange, substrate: green, housing attach area: black. Pixel array is in the mechanical center of the module in both cases.

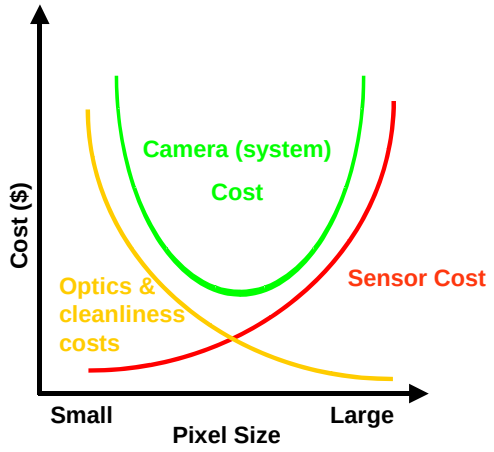

Figure 6. Camera module cost vs. pixel size

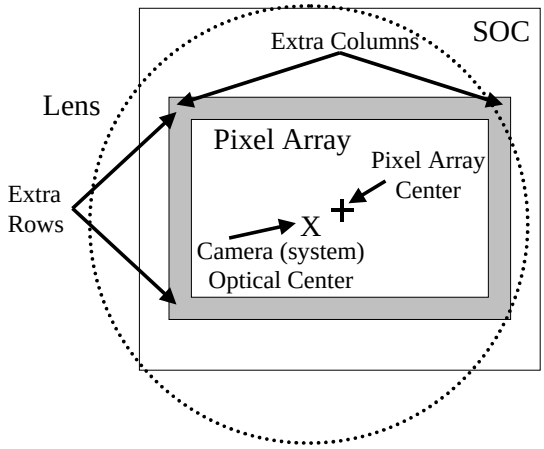

Figure 7. Camera Module (Top View) Illustrating Effect of Lens to SOC Misalignment

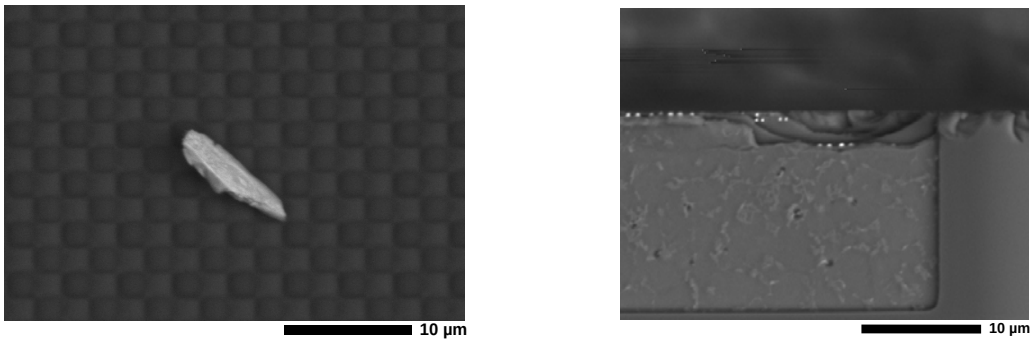

Figure 8. SEM image of particle on active pixel array after wafer washing, left. Image of saw street of die with particle, right.