71.2: *Distinguished Paper:* iMoD™ Display Manufacturing

Philip D. Floyd, David Heald, Brian Arbuckle, Alan Lewis, Manish Kothari, Brian J. Gally, Bill Cummings, B.R. Natarajan, Lauren Palmateer
QUALCOMM MEMS Technologies, Inc.
5775 Morehouse Drive, San Diego, CA 92121

Jan Bos, Daniel Chang, Jedi Chiang, Denny Chu, Li-Ming Wang, Edmon Pao, Fritz Su, Vincent Huang
QUALCOMM MEMS Technologies Taiwan, Ltd.
8F-1, 29, Puding Rd., Hsinchu, Taiwan

Wen-Jian Lin, Wen-Chung Tang, Jia-Jiun Yeh, Chen-Chun Chan, Fang-Ann Shu, Yuh-Diing Ju
Prime View International Co., Ltd.
3 Li Shin Rd. 1, Science-Based Industrial Park, Hsinchu, Taiwan

Abstract
QUALCOMM has developed and transferred to manufacturing iMoD Displays, a MEMS-based reflective display technology. The iMoD array architecture allows for development at wafer scale, yet easily scales-up to enable fabrication on flat-panel display (FPD) lines. In this paper, we will describe the device operation, process flow and fabrication, technology transfer issues, and display performance.

1. Introduction
Mobile electronic devices generally, and mobile wireless devices in particular, place exceptional demands on their displays. Applications such as video to wireless devices (QUALCOMM MediaFLO™) require Always-On™ displays, readable in a wide variety of viewing environments. Achieving this goal requires displays with low power consumption, excellent readability in direct sunlight, the ability to operate over a wide environmental range, and performance to handle multimedia content.

At QUALCOMM MEMS Technologies (QMT), we are developing and manufacturing a display that addresses these developing consumer needs. The iMoD display, a reflective display based on MEMS (micro-electro-mechanical-systems), offers all the benefits that consumers are looking for in their mobile devices—excellent readability, low power consumption, and the ability to handle multimedia content, resulting in an Always-On user experience.

The iMoD display is a high speed, electrostatically-actuated, bistable MEMS device built on a glass substrate [1] [2] [3]. An iMoD element consists of a suspended conductive membrane serving as a mirror, over a partially reflective optical stack. Interference between light reflected from the reflective membrane and from the partially reflective optical stack generates color.

Because color filters and polarizers are not necessary in iMoD displays, they are very bright as a result. This enables viewing in a wide variety of ambient light environments.

We will describe the manufacturing process of the iMoD display and implementation of the process in a flat-panel display fab, as well as the performance of encapsulated iMoD displays.

2. iMoD Display Operation
Optical Interference

Color is generated by the well-known principle of optical interference. iMoD elements can be described as two conductive reflectors separated by an air gap and a dielectric. The color is governed by the optical path length between the two mirrors. For displays, the gap is chosen so that colors throughout the visible spectrum are generated. To generate a low reflectivity state such as black, the reflectance peak is moved into the UV. [2][3] The results of using different gaps are shown in Figure 1.

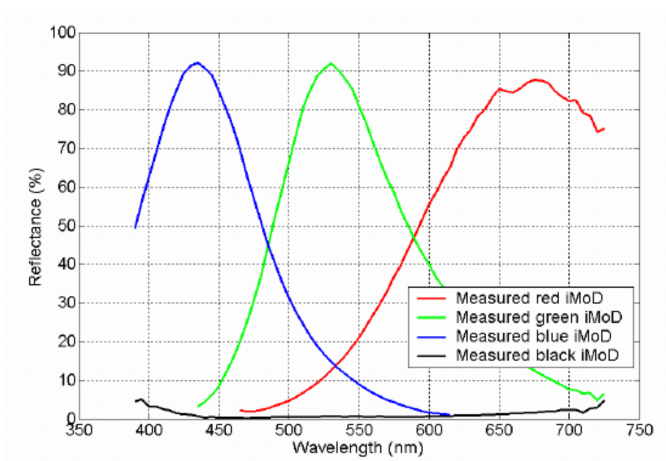

Figure 1. Optical spectra from iMoD elements designed to reflect in red, green, blue and black. The black state spectrum is at the bottom of the graph.

Electro-Mechanics

A distinguishing feature of iMoD technology is its bistability, which allows for data to be written and held with a modest bias voltage. The bistability is a consequence of the electro-mechanics of the iMoD elements. The iMoD elements can be modeled as a

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capacitor with one moving plate, suspended by a spring above an immobile plate.

A simple model of the system results in the plot of Fig. 2, in which the loops of the characteristic hysteresis curve are shown. The two stable states are two different membrane positions, each with a characteristic color.

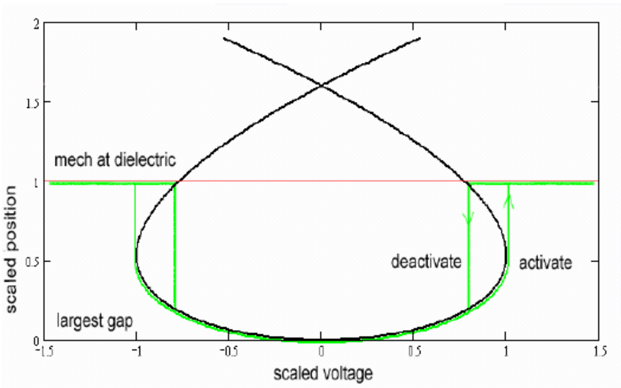

Figure 2 Plot of the solution balancing electrostatic force with restoration force for the movable membrane/mirror. The resulting hysteresis loop is plotted on top of the solution.

3. Process Architecture and Design

Array Processing

From its inception, the iMoD technology was intended to be built on large area substrates common in the LCD industry. This requires that we align materials and processes used with those used in LCD's. Examples are listed in Table 1.

Table 1 Materials used for LCD fabrication

Material	***Purpose***
Al, Al:Nd	Gate metal, Gate bus line
Ta, Mo-W, MoCr, Mo	Gate metal
ITO	Pixel electrode
SiNx	Passivation, gate dielectric
a-Si	Channel

Sacrificial Layer Etching

Sacrificial layer etching, used in MEMS technology, is significantly different from FPD fabrication processes. The iMoD element is a MEMS device; therefore it requires removal of a sacrificial layer to free mechanical elements to move.

Wet etching techniques require the removal of the wet etchant with other fluids and eventually sublimation to avoid irreversible collapse of the MEMS structure during the release process. To reduce the complexity of the release process and to address many process integration issues, we have chosen a gas-phase XeF_2 etch for release etching.

Encapsulation

The moveable membranes of iMoD arrays must be protected from particles, abrasion and moisture. It is possible for MEMS devices to become non-functional due to stiction of moving parts. Such stiction is often driven by water adsorption to surfaces of the MEMS devices, causing adjacent parts to stick together.

It is important to note that the highly robust iMoD array does not fail due to short-term exposure to ambient oxygen or air. However, the iMoD array requires a managed environment in order to maximize functionality and lifetime.

4. Process Transfer and Scale-Up

QMT conducts development using 6 inch (150 mm) glass wafers and standard semiconductor tools. A "Copy Exact" process transfer is not possible, since we do not develop iMoD™ technology on a FPD line. However, the majority of unit processes used to build iMoD arrays utilize similar physical principles to FPD processes. Therefore, we can consider the transfer as "Copy Smart." The tools, processes, and process integration used in development on 6 inch wafers, are mimicked with FPD tool sets.

Specifications are developed based on the construction and performance of the iMoD arrays built at wafer scale. These specifications become targets for the final large-area processes. The transfer focuses on some key areas, briefly described below.

High-level process matching

At its simplest process techniques are replicated as closely as possible from one fab to another, which is a straightforward way of meeting required specifications. However, this task can be complicated by the availability of a particular process in the large-area, target fab. It must be determined whether an existing process can be substituted, or if there is a need to introduce a new process and/or new tool to the target fab.

Material matching and characterization

Characterization of the electrical, mechanical, and optical properties of the material composing the iMoD display is required. This reveals any variations in expected material properties due to the difference in tools or deposition techniques used in the wafer-scale versus large-area equipment.

Large-area process development

The goal is to complete the process module using chosen material(s). This can be as straightforward as a set of experiments to optimize a process and hitting the required specifications. However, it can become more complex if the identical process tool or chemical does not exist at the target fab. Any changes must not affect the ability to hit a process specification and the resulting process must integrate with the other process modules.

5. Process Flow and Fabrication

The iMoD process flow is shown in the form of a flowchart in Figure 3. The process starts from bare Gen 2 (370 mm x 470 mm) glass and ends with etching of the sacrificial layer. The majority of the unit processes are similar to those used in FPD fabrication. The final iMoD structure is shown in cross section in Figure 4.

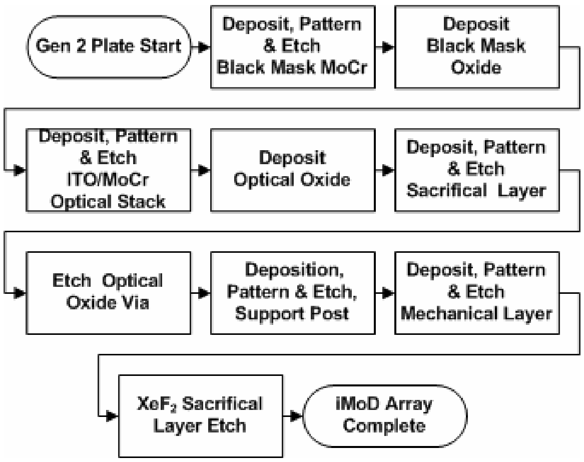

Figure 3 Process flow for iMoD™ array fabrication

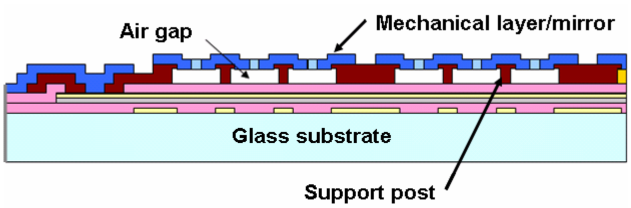

Figure 4 Cross-section of an iMoD pixel after completion of release etching

As shown above, the process consists of straightforward deposition, patterning and etching steps. However, there are some subtle differences in the flow as compared to, for example, TFT fabrication. The iMoD display utilizes multiple layers of different materials in a single deposition step. Because of the multiple depositions, care needs to be taken in the organization of the process line, to avoid deposition-related bottlenecks.

iMoD Display Encapsulation Requirements

Reliable iMoD display operation requires a dry, particle-free environment. The encapsulation only need manage the environment of the iMoD display; there is no requirement for hermetic packaging as with other MEMS-based devices. It is also important to note that the iMoD display can be transported under ambient conditions without damage to the device, and it is insensitive to oxygen.

The iMoD package must provide sufficient space so the mechanical elements are not hindered from motion. From a manufacturing perspective, the packaging process should be compatible with display industry processes and have the ability to scale to large product volume.

Product-driven packaging requirements include:

1. Thin form factor for portable display applications
2. Use of standard LCD driver interconnect technology
3. Reliability & reasonable lifetime for consumer applications

The form factor requirements drive solutions with commonality with LCD type packaging. Such packages use adhesive sealing with relatively thin backplates. The requirements for environmental management in the package leads to the inclusion of a desiccant. To maintain the required free space for mechanical motion, we choose a recessed backplate.

The basic outline of the package is shown in Figure 5. It consists of a glass backplate with a recess to hold a desiccant. The backplate is sealed to the iMoD array using an adhesive.

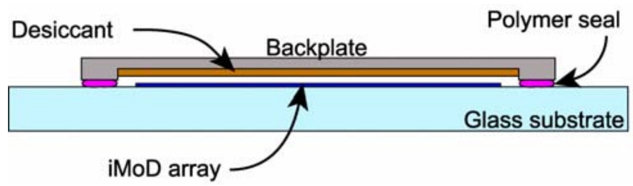

Figure 5 Cross-section diagram of encapsulated iMoD panel.

Encapsulation Engineering

Given the proper choice of adhesive seal thickness, package geometry and type of adhesive with low water vapor permeation, the flux of H_2O into the package will be continuously and effectively absorbed by the desiccant matrix. The internal package environment remains in equilibrium with the desiccant matrix until all the capacity of the desiccant is used up. The device will reach its end of life when the H_2O absorption capacity of the desiccant has been exceeded.

A simple model is compared to measured test structures and verifies the device geometry and choice of materials to achieve the required lifetimes. The model takes into account the amount of desiccant required to absorb the incoming water vapor flux over the lifetime of the display. The model is verified by accelerating the water vapor flux into the package using a thick (~500 um) seal and measuring weight gain of the package.

The result is a design with a relatively thin seal (10 um-30um), seal width of ~2 mm and required desiccant thickness of <0.2 mm. The model predicts a lifetime of 10 years at 40C/90 %RH.

Process Flow and Integration

The encapsulation process joins 370 mm x 470 mm iMoD array plates and large-area plates of recessed glass with desiccant applied. The glass is processed and assembled to create a biplane assembly which is subsequently singulated into encapsulated display panels. The assembly of the iMoD display to the recessed glass using an adhesive is accomplished in equipment built by DNK (Japan Science Engineering Co.).

Figure 6 iMoD display encapsulation tool

The flowchart of Figure 7 illustrates the encapsulation process.

The encapsulation process begins after etching of the sacrificial layer.

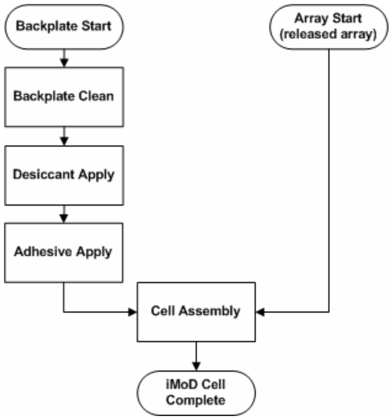

Figure 7 Flow chart of the process for encapsulation of iMoD array.

6. Array Performance

Initial characterization of an encapsulated panel consists of testing for shorts and opens in the array, as well as characterization of line resistances. Electro-optic characteristics are tested at both the panel and pixel level. Figure 8 (a) shows the hysteresis curve for iMoD pixels. By applying a pulse above the voltage actuation voltage, the panel is driven to a black state as shown in Figure 8 (b). Driving the display with a voltage less than the release voltage (lower voltage in the hysteresis curve) results in a bright state as shown in Figure 8 (c).

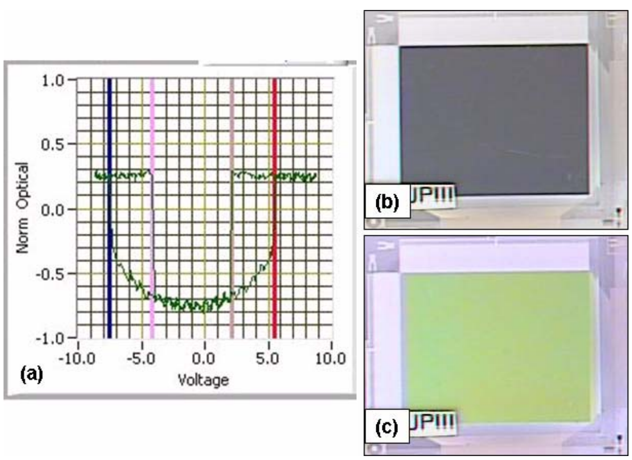

Figure 8 (a) Hysteresis curve of iMoD array pixels in a two-color iMoD display fabricated on a Gen 2 panel on FPD line. Figure 8 (b) & (c) Images of display panel driven into dark and bright states, respectively.

Once drivers are attached to the panel, we can drive the panels with content. An example is shown in Figure 9. The image is very high contrast, easily viewable in ambient lighting.

7. Conclusion

iMoD displays have been successfully fabricated and encapsulated on a commercial FPD line. We successfully scaled the process from wafer-scale to FPD format by careful design of the iMoD array architecture and judicious selection of materials and processes. The superior color, brightness and power consumption of iMoD displays will lead to acceptance for mobile display applications in the very near future.

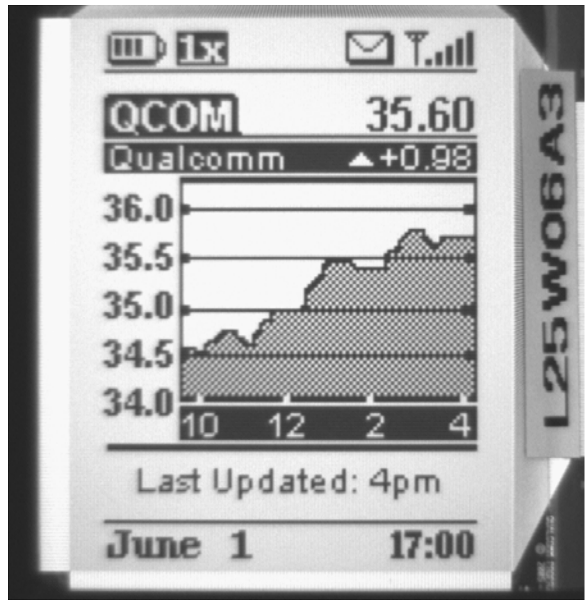

Figure 9 Complete iMoD display with driver, driven with content under general room illumination.

8. References

[1] M.W. Miles, "Digital Paper ™ :Reflective Displays Using Interferometric Modulation", SID 2000 Digest, p. 32 (2000)

[2] M. Miles, E. Larson, C. Chui, M. Kothari, B. Gally, and J. Batey, "Digital Paper™ for Reflective Displays", SID Symposium Digest 33, 115 (2002)

[3] Brian J. Gally, "Wide-Gamut Color Reflective Displays Using iMoD™ Interference Technology", SID Symposium Digest 35, 654 (2004)