Proceedings of the Asia Display 2007, SID, Volume 1, pp 107 - 112

Advanced Processes for MEMS-based Displays

Ana Londergan, Evgeni Gousev and Clarence Chui
QUALCOMM MEMS Technologies, MEMS Research and Innovation Center, 2581 Junction Avenue, San Jose, CA 95134, USA,
e-mail: alondergan@qualcomm.com

Abstract: QUALCOMM MEMS Technologies is developing and commercializing a revolutionary MEMS-based technology for low power refractive displays. Concurrent with product development and manufacturing engineering in a TFT foundary in Taiwan, there are significant research activities in a state-of-the-art MEMS Research and Innovation Center in San Jose, California , to enable future technology generations. In this paper, we will overview iMoD fundamentals and the current status of the technology as well as discuss some research projects in the areas of advanced materials, processes and concepts for future MEMS displays manufacturing.

Key Words: Reflective displays, MEMS displays, iMoD, Nanoengineering, ALD.

1 Introduction

Wireless communications are an essential and continuously expanding part of modern life. In particular, portable electronic devices, such as cell phones are rapidly evolving into “smart phones”, offering increasing functionality, and supporting multimedia and a variety of new emerging applications. This presents a number of challenging requirements on the display module, such as low power consumption, video quality speed, and viewability in a broad range of lighting conditions.

QUALCOMM has chosen the iMoD reflective display technology to meet these demands and carry the mobile communications well into the 21st century [1, 2]. The QUALCOMM Interferometric Modulator (iMoD) display is an electrostatically actuated, bistable micro eclectromechanical system (MEMS) device.

The iMoD technology employs optical interference, which is an inherently efficient way to create high brightness color as no filters or polarizers are used [1]. An iMoD element is comprised of a conductive reflective membrane (mirror) suspended over a thin film stack formed on a glass substrate (Fig. 1a). The layers in the thin film stack can be grouped in two functional subsets: conductive partially reflective stack and optical dielectric. In essence, the iMoD element is an optically resonant cavity defined by the two conductive reflectors, which are separated by an air gap and a dielectric [1, 2]. Thus, the color seen by the viewer is associated with the resonant wavelength, determined by the optical path length between the two reflectors. RGB pixels have iMoD elements with different air gaps designed to reflect in the red, green, and blue wavelength, respectively.

Black is perceived when a small optical path length is produced, which moves the resonant wavelength into the UV part of the spectrum. Switching between a bright color state and a black state is where the MEMS functionality of the iMoD element comes into play. The application of a voltage between the two reflectors is used to “collapse” the pixel into the black state (Fig. 1b). Visible light wavelengths are on the nanometer scale (i.e., 380 nm to 780 nm), thus the air gap is <1µm wide. Accordingly, the iMoD reflective membrane (mirror) moves only a short distance, a few hundred nm, to switch. This switching is extremely fast, on the order of tens of µs rendering the iMoD display video-rate capability.

Another key advantage derived from the iMoD’s MEMS properties is bistability. Bistability stems from the inherent competition between the linear restorative forces of the mechanical membrane and the nonlinear forces of the applied electrostatic field [2]. The resulting opto-mechanical hysteresis provides a built-in “memory”, which enables the elimination of the TFT array conventionally used for LCD display addressing. Further, the bistability allows for data to be written and held with a low bias voltage, resulting in exceptionally low power consumption.

In summary, the MEMS functionality of the iMoD displays provides color selection, modulation and memory. Currently in development for applications such as wireless phones and other portable devices, iMoD displays enable an Always-On™ experience supporting multimedia applications with ultra-low power consumption, fast switching times and day light viewability.

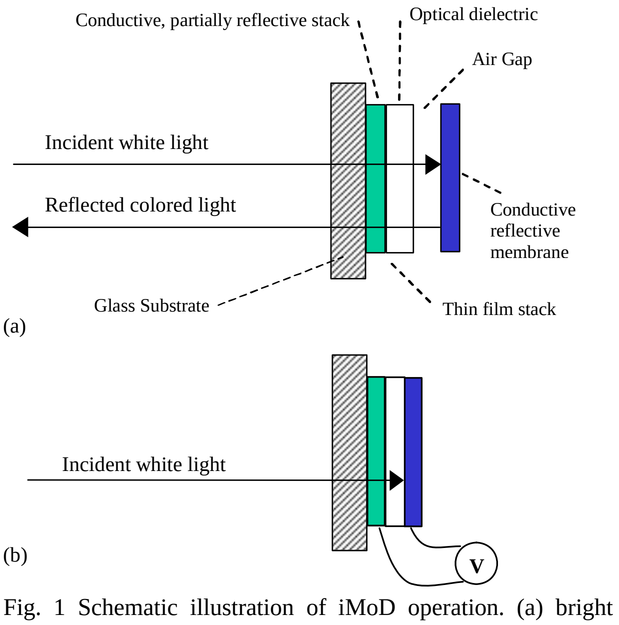

Fig. 1 Schematic illustration of iMoD operation. (a) bright “open” state, (b) black “collapsed” state

2 Manufacturing, Technology Transfer and R&D

QUALCOMM’s iMoD display manufacturing is an example of manufacturing that requires a mixture of conventional and new techniques. Similarly to other displays, iMoD displays, are made using repeated thin film deposition / pattern / etch cycles on thin glass plates [2]. One significant difference from FPD fabrication processes is the sacrificial layer removal, used in MEMS technology to free the mechanical elements to move. iMoD displays are encapsulated following the sacrificial layer removal. Encapsulation is important to protect the movable membranes from particles, abrasion and moisture [1].

iMoD displays have been successfully fabricated and encapsulated on a commercial large area glass TFT FPD line [1, 2]. Generally, materials common to LCD manufacturing and mature LCD Fab tools are used.

QUALCOMM’s iMoD technology opens up a new world of display innovations and opportunities for exploration. Ongoing R&D activities are essential for future technologies and products. To support these activities QUALCOMM has built and operates a MEMS Research and Innovation Center (MRIC) including a state-of-the-art fab facility in San Jose, California. Advanced materials, processes and concepts are researched for future MEMS displays manufacturing. Nanotechnology tools and approaches are leveraged.

It is important to note that there is certain freedom in the material choices for the iMoD thin film stack. This provides the opportunity to match and tune a particular iMoD process to a particular manufacturing facility, such as an LCD fab with minimal modifications to the fab. Yield and performance advantages that could be realized through the introduction of new materials and processes are discussed in the following sections.

3 iMoD MEMS-based Direct View Displays

3.1 iMoD is a MEMS Device

As discussed in the first section, the iMoD is an electrostatically actuated, bistable MEMS device. The application of voltage between the two iMoD reflectors creates an electrostatic field. Depending on the applied voltage, the iMoD reflective membrane (mirror) is either in the bright “open” state or in the black “collapsed” state. In one simple iMoD architecture the mirror “rests” on the dielectric layer in the collapsed state. This is known as a capacitive switch MEMS device. The dielectric layer serves as a mechanical stop for the mirror in the down state and ensures electrical insulation between the reflectors. Consequently, high quality of the dielectric is of critical importance for the optimal device operation. Thus the deposition of high quality dielectrics is addressed in greater details in the Section 4.

The mirror moves only a few hundred nm (<1 µm), to switch. In contrast, the lateral dimensions of the mirror are determined by the given subpixel design and are generally on the order of tens to hundreds of microns. Consequently, the internal surface area of the iMoD cavity and the contact area in the collapsed state are relatively large. Therefore, as in any typical nanotechnology device, the surfaces and interfaces are of great importance.

iMoD devices are relatively robust and good reliability is fabricated with the use of higher quality dielectrics, surface and interface control and adequate packaging.

3.2 iMoD is an Optical Device

The iMoD technology employs optical interference to create vibrant color. Visible light wavelengths are on the nanometer scale (i.e., 380 nm to 780 nm), thus nano scale engineering and control of the optical path lengths for the RGB pixels is applied. The optical path length is defined by the air gap and the dielectric layer. Accordingly, tight control of the dielectic films thickness, uniformity and index of refraction is required for optimal, uniform optical performance over the entire large area glass substrate.

Using the same thin film stack for the three RGB subpixels is simpler and cheaper to manufacture and capable of generating high optical performance. However, significant improvements in display image quality performance are possible by customizing the design for each sub-pixel, especially the red color [3]. This adds flexibility in the selection of the hue of the primary colors and the resulting color gamut of the display. High performance displays with improvements in the color gamut, reflectance and contrast ratio, can be fabricated by, for example, the addition of a metallic thin film layer in the red sub-pixel stack. However, some of these materials are not commonly found in LCD fabs. The need for new, advanced materials and processes on large area glass substrates is further addressed in the next section.

3.3 Films and Processing

Generally, materials common in the LCD industry and mature LCD Fab tools are used in iMoD displays manufacturing on large area glass. As iMoD technology matures, new materials and advanced processes will be introduced enabling higher performance, more functionality, better level of integration and reduced cost. There is a variety of alternative materials with compelling optical properties and advanced fabrication processes common in the electronics industry that could be considered for transfer to large area glass. Yield and performance advantages could be realized through the introduction of new materials and processes at the cost of additional initial investment.

Most films used in iMoD fabrication are grown by sputtering or Plasma Enhanced Chemical Vapor Deposition (PECVD). In a PECVD process, the film constituents come form molecular precursors that are delivered to the substrate surface and plasma is used as an additional energy source. PECVD is commonly employed for the deposition of SiNx, SiO_2, and amorphous Si for the TFT LCD manufacturing.

Novel techniques are under investigation for better quality dielectrics for future high-end display technologies [4]. One such technique is Atomic Layer Deposition (ALD). Dielectric films can also be deposited using ALD with precise control and quality superior than conventional sputtered or PECVD films [5]. This generally transtates into higher yeilds in addition to gains in performace. ALD is a powerful nanotechnology enginering tool that can be used to enhance various areas of iMoD and other MEMS devices and displays manufacturing in general.

4 Atomic Layer Deposition Technology

4.1 Principles of operation, thickness and uniformity control

ALD is a variant of CVD where the molecular precursors are delivered into the deposition chamber one at a time and removed before the subsequent precursor exposures (Fig. 2). Each precursor individually reacts with the substrate surface. A key characteristic of ALD reactions is their self limiting behavior: the film growth stops as soon as the precursor reaction with the substrate surface is complete and than recommences only after the second precursor is introduced. Accordingly, the ALD film grows in "steps" of ~ 1 Å at a time and the thickness is a liner function of the number of precursor exposures (pulses). The alternating precursor pulses are separated by purge periods to remove un-reacted precursors and by-products.

These characteristics make ALD a powerful thin film nano-engineering tool. Key advantages of the ALD deposition method are summarized below:

- Precise "digital" thickness control: at the atomic level
- Excellent uniformity over the entire substrate area due to the self limiting behavior
- 100% step coverage (SC) on 3D shapes
- Enables film engineering: robust composition control
- Low defect and pinhole density, pinhole free films are possible.
- Low deposition temperature: 80 to 350°C (compatible with plastics)
- Wide process window; excellent repeatability
- Process scalability to large area substrates

ALD films typically exhibit superior performance (key process features and film quality) compared to other deposition methods, therefore, higher yields are commonly achieved too. These features made the ALD technology very popular in the semiconductor ULSI manufacturing over the past 5 years, as discussed in the following sections.

Numerous materials have been deposited using ALD and the list is continuously growing. For quick reference, example materials are listed in Table I. Comprehensive review of the ALD technology can be found, for example, in Ref. [6]. For up to date overview of ALD technology, applictions and state-of-the-art nanoengineering using ALD see Ref. [7].

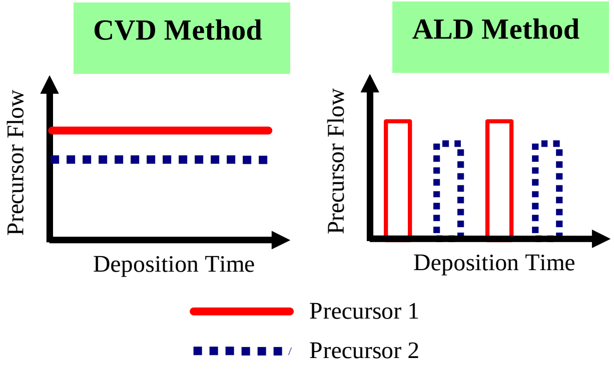

Figure 2 Schematic illustration of the CVD and ALD methods

Oxides (diel.)	Al_2O_3, HfO_2, SiO_2, ZnO, ZrO_2, TiO_2, etc.
TCOs	ITO, In_2O_3, SnO_2, ZnO (Al, B, Ga), NiO
Nitrides	AlN, TiN, TaNx, HfN, GaN, SiNx, etc.
Metals	W, Pt, Ru , etc.
Sulfides	ZnS, SrS, CdS, etc.
Composites	WCN, HfSiOx , etc.
Doped Films	ZnS (Mn); SrS (Ce), etc.

Table I Example Materials Deposited by ALD

4.2 ALD offers advantages to other display technologies: a retrospective

Interestingly ALD (named Atomic Layer Epitaxy, ALE) was developed in the early 70s as a solution to the challenging material requirements for the thin film electroluminescent (TFEL) FPDs [6]. The ALD films met the requirements of high breakdown strength, low leakage at ~200V AC, and low pinhole density and were introduced into TFEL display manufacturing circa 1985. ZnS:Mn, Al_2O_3 and Al_2O_3/TiO_2 (ATO) are typical ALD materials used by the industry [6]. ALD Al_2O_3 is also used for Na diffusion barrier, making the cost -effective manufacturing on soda lime glass possible.

4.3 Leveraging learning from the Semiconductor Manufacturing Industry

In the 90-s ALD was a new, disruptive technology, for the semiconductor industry, and is now adopted in manufacturing. The interest in ALD was fueled by the need to keep up with the Moore's Law of continuous reduction of device dimensions to improve performance and lower costs at the 90 nm node and beyond. For example, capacitance enhancement in DRAM cells is achieved trough increasing the surface area of the capacitors and/or the dielectric constant of the oxide [8]. To accomplish that, hemispherical grain Si (HSG) is used and the aspect ratios of the storage capacitors are increasing, with deep trench capacitors approaching 100:1 aspect ratios. ALD is the only technique capable of depositing high-k dielectrics into these features with the required uniformity and conformality. Accordingly, major DRAM manufacturers have adopted ALD into production.

ALD is also expected to play an increasingly important role in other areas of IC manufacturing as device dimensions continue to shrink. ALD W is used to provide thin, conformal nucleation layer for CVD W in higher aspect ratio contacts. Conductive materials, such as TaNx, TiN, WCN, Pt, Ru, etc., are explored for ultra-thin diffusion barriers for Cu metallization, capacitor and gate electrodes [7]. High dielectric constant materials, such as HfO_2, $HfSiO_x$, HfSiON, ZrO_2 are intensively researched for gate oxides in next generations high performance transistors [9].

The path to maturity took time and investment and yielded learning and cost competitive advantages. 10 years ago ALD was considered exotic and "too slow". Today, major semiconductor deposition equipment vendors offer ALD tools and many are with competitive throughput.

The ALD know how and deposition equipment availability is enabling other technologies. For example, hard disc drives manufacturing is using the pin hole-free ALD Al_2O_3 thin films to provide electrical insulation in magnetic recording read heads. Introduction in production was quick, due to dramatic, immediate yield improvement over PVD Al_2O_3 [10].

Presently ALD is gaining interest in a broad variety of nanotechnology, nanoscience and industrial applications [7].

4.4 Nano-control by ALD

Nanotechnology is the Future. Research on utilizing nanotechnology for various (communications, solar and fuel cells, medical, biotech, etc.) applications is rapidly expanding. For example, nanotubes and nanowires are studied for use in RF components relevant to telecommunications and nano emissive displays.

ALD with its films engineering on the atomic level capability holds great promise for future applications in nano-scale engineering.

For instance, the conformality and multi-functionality of ALD films make them appealing for micro- and nano-scale electro-mechanical devices (NEMS) [11]. ALD is under evaluation as a potential solution to problems related to friction, stiction, etc. ALD of Al_2O_3/ZnO_2 alloys and nanolayes with precise composition control are studied for charge dissipation layers. Additionally, thin ALD films, such as W, may be used as structural components of nanometer-scale devices. The reliable, high-density coatings of hydrophobic and hydrophilic ALD monolayers may replace self-assembled monolayer (SAM) coatings commonly used for BioMEMS and protein-based nanosensors and nano-actuators.

Conformal ALD of Al_2O_3 and HfO_2 on functionalized, suspended single-walled carbon nanotubes (SWNTs) has been demonstrated [12].

4.5 ALD of Transparent Conductive Oxides

ALD is suited for the deposition of composite oxide materials with precise composition control and excellent uniformity over various substrates. As seen in Table 1 various transparent conductive oxides (TCO) have been deposited by ALD. There is growing interest in using ALD of ZnO(Al) for TFT and solar cell applications, where the lower material cost and conformality make it very attractive.

4.6 ALD on large area glass substrates

While the ALD technology is reaching “production-ready” maturity in the semiconductor manufacturing on 300 mm round wafers, it is in early stages with respect to large area glass.

Smaller size glass is routinely processed in ALD batch tools in TFEL FPD display manufacturing since 1985 [6]. ALD/PECVD tool and process capability for 370mm x 470mm glass size was recently reported [5]. The ALD SiO_2 film uniformity was superior to PECVD, at +/-5% and +/-10 %, respectively. Due to the low deposition rate of ~ 1 Å/ALD cycle of the ALD SiO_2, a more practical approach of using 2 nm ALD/100nm PECVD film stack is proposed for gate dielectric in high performance low temperature poly-Si (LTPS) TFT. The ALD/PECVD stacked insulator had very good electrical properties: interface trap density of $1x10^{11}$ $cm^{-2}eV^{-1}$, leakage current: $1x10^{-6}A/cm^{-2}$, and breakdown: 7.5 $MV\text{-}cm^{-1}$.

One of the biggest drawbacks of ALD is the relatively low deposition rate, ~ 1 Å per ALD cycle. Therefore, batch ALD tools where multiple glass plates are deposited simultaneously or faster ALD processes are preferred to realize lower cost.

5 ALD for Advanced Display Technologies: Potential Benefits

ALD technology can bring great benefits to advanced display manifacturing by providing a variety of high quality insulating and conducting materials. ALD of alternative TCOs may ease the dependency of the industry on ITO. ALD gate dielectrics with improved electrical quality and dramatically reduced interface defect density can enable high performance LTPS-TFTs for future System-on-Panel (SoP) applications.

ALD Al_2O_3 is under evaluation for advanced OLEDS encapsulation. Robust, no dessicant thin-film encapsulation method for top-emitter OLEDs that utilizes a layer of ALD Al_2O_3 as the primary moisture barrier was reported [13]. No significant device degradation caused by moisture was observed after >1000 h in 85 °C and 85% RH testing. To overcome the ALD throughput limitation, myltilayered structures with alternating thin ALD layers are explored with promissing results. For example, encapsulation on an OLED device on glass substrate using 200nm PECVD SiNx / 30nm ALD Al_2O_3 (90ºC)/ PECVD SiNx / 30nm ALD Al_2O_3 was demonstrated [14].

The good uniformity and thickness control, low defect and pinhole density and high electrical quality of ALD films make ALD an attractive technology for advanced iMoD displays. For example, IMoDs fabricated at MRIC with optical dielectric deposited by ALD had performance comparable or better than baseline iMoDs. Test metal-insulator-metal (MIM) capasitors showed low leakage current and ~25% improvement of breakdown voltage. ALD SiO_2 films with uniformity of 6% 3-sigma, relatively fast deposition rate of 25 Å/min, and breakdown field of >10 MV-cm were used. Other insulating and conducting materials by ALD are under evaluation.

6 Summary

Innovations in materials and deposition techniques are some of the key R&D areas to enable future generations of advanced displays. In this paper we introduce one novel promising technology, ALD, and describe multiple benefits it may offer to the display community, both for conventional display manufacturing and emerging technologies. Better quality dielectric materials will enable dielectric scaling for high performance TFTs. Emerging display technologies, such as iMoD and OLEDS will also benefit.

References

[1] J.B. Sampsell, MEMS-Based Display Technology Drives Next-Generation FPDs for Mobile Applications, Information Display, Vol. 22, No. 6, 2006, p.24-28

[2] P.D. Floyd et. al., iMoD Display Manufacturing, Proc. SID, Vol. 37, 2006, p.1980-1983

[3] B.J. Gally et. al., Wide-Gamut Color Reflective Displays Using iMoD Interference Technology, Proc. SID, Vol. 35, 2004, p. 654-657

[4] A. T. Voutsas, Poly-Si TFT Technology: Advances in Material, Process and Device Technology, ECS Transactions, Vol. 3, No 8, 2006, p. 157

[5] K. Murata et. al., Development of ALD/PECVD Reactor for High Quality LTPS-TFTs Insulator, ECS Transactions, Vol. 3, No 8, 2006, p. 101-106

[6] M. Ritala and M. Leskela, Atomic Layer Deposition, Chapter 2 in Handbook of Thin Film Materials, Vol. 1, Academic Press, 2002, p. 103

[7] Atomic Layer Deposition Applications II, Eds. A.R. Londergan et. al., ECS Transactions, Vol. 3, 2007

[8] M. Gutsche et. al, Capacitance enhancement techniques for sub-100nm trench DRAMs, IEDM Tech.Dig., 2001, p. 411

[9] R.M. Wallace and G.D. Wilk, High-k dielectric materials for microelectronics, Critical Reviews in Solid State and Materials Sciences, Vol. 28, 2003, p. 231 -285

[10] Wei Xiong et. al., Ultra-thin ALD Alumina Reader Gaps for High Density Recording Heads, MMM Conf. 2001, Session HP-03

[11] Y.-J. Changa et. al., Atomic Layer Deposited Films for Micro- and Nano-scale Electro-Mechanical Systems, in [7]

[12] D.B. Farmera et. al., ALD of High-k Dielectrics on Suspended Functionalized SWNTs, Electrochemical and Solid-State Letters, Vol. 8, No 4, 2005, G89-G91

[13] A.P. Ghosh et. al., Thin-film encapsulation of organic light-emitting devices, Appl.Phys.Lett, 86, 2005, 223503

[14] S.-H. Ko Park et. al., Ultrathin Film Encapsulation of an OLED by ALD, Electrochemical and Solid-State Letters, Vol. 8, No 2, 2005, H21-H23