MEMS: Making Micro Machines
Script with Chapters (Scene Selections)

Chapter 1 – Introduction to MEMS

1. Mechanical ingenuity combined with micro or nano manufacturing methods has evolved into Microelectromechanical Systems known as MEMS, micro machines, or microsystems.

2. These tiny micro machines have both mechanical and electrical components that are either side-by-side within a single package, or integrated on a single chip. In their mechanical function they move masses, liquids and light, or sense vibration and pressure. In their electronic function they convert mechanical information to digital information and digital information to mechanical motion.

3. If microprocessors and microcontrollers are the brains of electronic products, then MEMS are the eyes, ears, nose, and physical extensions that provide information to that brain.

4. MEMS are all around us in our digitized world. In the thermal inkjet printhead, hundreds of microfluidic devices direct the flow of ink and eject thousands of tiny drops a second. In medicine, microfluidic pumps help people monitor insulin levels. Lab-on-a-chip provides tiny channels leading to mini labs used in chemical and biomedical research.

5. In Digital Light Processing, MEMS devices project the images seen at theaters. Inside this theater projector are DLP chips that contain millions of microscopic mirrors. Smaller DLP chips are also found in televisions and business projectors.

6. In cars MEMS pressure sensors monitor things like engine control to improve fuel efficiency. In camcorders, MEMS accelerometers stabilize the image. In football they monitor the effects of impact on a player's head. In gaming accelerometers allow us to be active players. They're also used in cell phones and GPS systems. The combination of MEMS gyroscopes and accelerometers are found in the segway and the space shuttle.

7. MEMS are an international enterprise. In today's global economy a MEMS device is often researched, designed, manufactured, and packaged by staff in different countries around the world.

8. While there are many types of MEMS devices three important catagories are microfluidics, optical MEMS, and sensors.

FABRICATION (Thermal Inkjet Printhead)

Chapter 2 – Inkjet Printheads

9. To see how these devices are fabricated, let's begin at Hewlett Packard's facility where the inkjet printhead is manufactured

10. MEMS are fabricated in various ways depending on their application. With silicon based MEMS, there are two major types of micromachining.

11. Surface Micromachining uses semiconductor processes like deposition, photolithography, etch and ion implantation to create the MEMS structure. These processes are similar to making computer chips and use some of the same equipment. In Bulk Micromachining, the silicon wafer itself is bulk etched to create the MEMS device components within the wafer.

12. The thermal inkjet printhead contains hundreds of microscopic MEMS devices typically fabricated in pairs of columns that surround an ink supply manifold.

13. Each device has a nozzle, a chamber, a resistor and a slot that connects it to the ink channel.

14. When current is applied, the resistor heats to boiling temperatures. It vaporizes the first layer of ink into a gas bubble that acts like a piston to eject the ink through the nozzle.

15. With the current off, the collapsing bubble drops back onto the resistor surface. The ink flows in and refills the chamber. Capillary forces pin the ink back at the nozzle's surface preventing it from flowing out until the resistor fires again.

16. Inkjet printheads are integrated devices. Both the MEMS devices and the CMOS circuitry, which provides the electrical current, are fabricated at the same time. Beneath these rows are the transistors, which have already been built. In this video we'll take a close look at how the MEMS devices are created from bare crystalline silicon.

17. The materials used in the creation of an inkjet printhead must withstand high heat, high duty cycles, and liquid environments containing acidic and basic inks. Therefore these materials are selected for their electrical, mechanical, and chemical properties.

Chapter 3 – Building the Thermal Resistors

18. Before the resistors are built, insulation is needed to protect the wafer. In this chemical vapor deposition system TEOS, a vaporized liquid that contains silicate, is used to deposit a silicon dioxide layer at low temperatures. Temperatures higher than 400 degrees Celsius would alter the aluminum copper used for the integrated circuits on other parts of the wafer.

19. Inside the CVD chamber TEOS reacts with oxygen to form silicon dioxide on the bare silicon surface. This silicon dioxide layer insulates the silicon wafer from the firing resistor.

20. The wafers move on to a metal deposition system where a conductive layer that will provide leads to the resistor will be deposited. First the wafers are conditioned by undergoing a physical sputter with Argon to remove any oxides or trace conductors. Then the wafers move to the metal deposition chamber. Here sputtering is used to transfer metal from a target to a layer of an aluminum copper alloy on the wafer.

21. Photolithography is used to pattern the metal layer. As we see here, the exposure system is next to the coat, develop, and bake track system. As the wafer spins a positive photo resist spreads across the wafer. The final spin speed of the wafer determines the specific thickness of the resist.

22. A tiny solvent stream removes the resist bead that forms along the edge. This prevents particle contamination when a wafer touches the cassettes or other tooling.

23. From the back of the track system, we see the wafers move to a hot plate where they are baked to remove most of the solvent.

24. Wafers then move into the I-line stepper. Here, a light source of a specific wavelength filters through a mask and a lens to expose the wafer. The resist is positive. The areas exposed to light are changed

chemically. The wafers move back to the track system. Here developer is puddled onto the wafer, and the exposed areas are rinsed away.

25. To insure quality, measuring feature size is important throughout the process. This SEM, or scanning electron microscope, is measuring the dimensions produced by the photo resist process.

26. The exposed metal will now be etched using plasma. In this chamber chlorine based and inert gases etch the aluminum copper alloy. This defines the resistor leads and removes the highly conductive aluminum copper layer from the area where the resistor material will be. While still under vacuum, the wafer moves to the ash chamber where the photo resist and etch residues are evaporated and pumped away.

27. The resistor metal in now deposited. After the wafer's surface is conditioned it goes to the sputter chamber where a thin layer of resistor metal is deposited.

28. Photolithography once again patterns the resistor metal layer.

29. In the plasma etch system the resistor metal layer is etched from unwanted regions. When current is eventually forced from two metal layers to one thin metal layer, it will create the heat that fires the resistors. A thin-film stack of three layers will now be deposited on the resistors to provide electrical, chemical and mechanical protection.

30. This system deposits the first two dielectric layers over the resistor. The first layer will provide electrical isolation between the ink and the firing resistor. In the same chamber, new gases deposit the second layer, which protects against the corrosive chemical attack from the ink.

31. The third protective layer is metallic so it can resist the mechanical forces of the collapsing bubble. The wafers go into a sputter etch chamber to prepare the surface and then into a sputter deposition chamber where a thin metal layer is deposited.

<u>Chapter 4 – Building the Chamber Walls</u>

32. Now that the resistors are protected, the chamber walls where the vapor bubble forms are built. The wafers are washed and prepped. A de-ionized water and ozone treatment removes any residual

33. The deposition of barrier material used for the chamber walls is similar to the photolithography process. As the wafer spins, a thick negative resist-like material is spiraled onto the wafer. In soft bake, the solvent is slowly driven out to "set" the barrier material and make it more uniform.

34. In this bake and expose system, the wafers go directly to the stepper where they are exposed. As a negative resist, the barrier material exposed to light forms a polymer and hardens. Because this resist is so thick, the exposure times are much longer than for standard photo resist. After exposure, the wafers move to the bake ovens. The areas exposed to light induce cross-linking and become a permanent part of the chamber.

35. The non-exposed areas are removed when developed. Instead of the usual puddle develop, spray develop is used here. Spraying droplets of developer provides a higher surface area that can attack the thick barrier material more easily.

36. A big open chamber now exists. We can see that small pillars have also been created from the barrier material. These pillars at the entrance to the chamber serve as a filter to block particles that might be in the ink from clogging the nozzle.

37. After develop, the wafers are placed in an oven, exposed to higher temperatures and allowed to cure. Thickness measurements are made after each layer is cured.

38. A thick photo resist resin, called a sacrificial wax, is spiraled onto the wafer and spun. The wax fills the cavity and covers the entire wafer. A soft bake sets the wax and a portion of it is removed to bring it flush with the chamber surface. The wax holds up the shape of the chamber as the building process continues.

<u>Chapter 5 – Creating the Nozzles</u>

39. In a dry process a layer of barrier material is pressed onto the wafers to create the nozzles. The nozzle material on this roll is sandwiched between two protective sheets of carrier films. The dry application will minimize the interaction between the nozzle layer and the sacrificial wax. Here, the bottom carrier film has been peeled away, and we see the nozzle material placed directly on the wafer.
materials that might remain on the surface from previous steps.

40. After the dry film is applied, a blade cuts around the remaining films and a new layer is prepared for the next wafer.

41. The robot moves the wafer with the nozzle material and its carrier film to the next stage.

42. In a separate tool, the carrier film is removed. A strip of tape is rolled across the wafer and a pick-up roll lifts the carrier film off.

43. Photolithography is now used to create the nozzle orifice. The exposed areas become cross-linked and remain a permanent part of the printhead. When developed, the unexposed nozzle material and the sacrificial wax are removed.

44. The wafers undergo a final cure.

45. To create the channels the inks will flow through, a laser and etch process forms a trench between two rows of nozzles. Inside the laser system, the wafers are placed backside up. A pulsating laser scans the back of the wafer and defines the dimensions of the slot. Without breaking through the silicon, it then drills a deep narrow trench within the slot.

46. The final slot shape is created in a bulk etch process. In this anisotropic etch, chemicals such as KOH and TMAH etch the silicon crystal and remove the remaining thin silicon layer left after laser micromachining.

47. Wafers are automatically mounted onto a ring and tape. This holds the die in place as the wafer is sawed into individual units.

48. Following singulation, the wafers are rinsed and dried to remove any particulates.

49. In a final visual inspection only the functioning die are examined before they are shipped. The camera on the microscope is programmed to recognize certain patterns. It highlights defects for the operator who then confirms or rejects them.

50. The sawed wafers are packed and shipped to various HP sites. There, the good die will be attached to a pen body like this one, which is becoming a permanent fixture in printers today.

OPTICAL MEMS

<u>Chapter 6 – Digital Mirror Device (DMD)</u>

51. Optical MEMS manipulate light. One of the most common is the Digital Micromirror Device, or DMD, which is the key component of the DLP technology found in high definition projection systems.

52. This cinema device contains 2.2 million microscopic mirrors known as pixels. Rows and rows of these tiny mirrors tilt ON and OFF thousands of times a second in response to digital signals. When a mirror is ON, it reflects one pixel of source light through a lens, which projects that pixel onto a screen.

53. A cross section view of the MEMS super structure shows how an individual mirror works. Part of the mirror is a U-shaped post that is attached to a solid plate known as a yoke. The yoke is attached to a suspended flexible hinge. When "ON" the hinge allows the yoke and mirror to tilt in response to electrical signals from the CMOS circuit beneath it.

54. DLP fabrication begins on a standard three metal layer CMOS SRAM wafer that already contains the circuitry that provides bias voltages to the individual mirrors.

55. Photo resist is deposited as a temporary spacer.

56. Vias provide access to the CMOS circuitry.

57. A layer of aluminum creates the hinge structure and its two posts, which allow the mirrors to move.

58. A silicon dioxide hard mask is patterned.

59. To form the yoke element, a layer of aluminum alloy is deposited.

60. A second silicon dioxide hard mask is created to protect sections of the yoke.

61. The exposed yoke and oxides are etched leaving a hinge that is continuous across the structure from post to post and which is attached to the yoke.

62. A second sacrificial layer of photo resist is deposited and patterned.

63. A final layer of aluminum alloy creates the support post and the mirrors on top.

64. An oxide layer is deposited and patterned.

65. The aluminum is etched and the oxide layer is removed. This creates the individual pixel mirrors attached to the yoke.

66. A final layer of resist is spread across the wafer. This protects the mirrors as they travel to different parts of the world where the DLP chips are packaged and tested.

PACKAGING (DMD Chips)

Chapter 7 – Packaging: DMD Chips

67. To understand how challenging it is to package devices with such tiny moving mechanical components let's go to Texas Instruments and see how DMD chips are packaged.

68. The packaging process begins with the removal of the spacers and protective photo resist. In a plasma strip system the photoresist is evaporated from the top, sides, and bottom of the mirrors.

69. This leaves the open spaces that will allow the mirror to tilt. As with all MEMS, these mirrors are mechanical structures that need to be protected.

70. So first, a protective window is bonded onto the wafer. These windows, with thin rectangular glass frames, have an anti reflective coat that enhances the transmission of light. They also have getter strips that absorb moisture. These windows will provide a protective, airtight, environment yet maintain optical transparency.

71. Meanwhile, the wafers go into an epoxy station. Here, clear epoxy is placed around the edges of each device.

72. The wafers with epoxy, and the windows with frames, are loaded onto a tool where they will be bonded together.

73. After the windows are aligned, they are flipped so the windows are up. The wafers, with epoxy around each die, are also aligned and placed beneath the windows. Light pressure is applied to hold the two together.

74. The glued wafer and window are then transferred to the bonding chamber where ultra violet light, heat, and pressure are applied in a vacuum. This bonds the windows to the CMOS wafer and hermetically seals the MEMS structures.

75. The bonded wafers now go into bake ovens where a thermal cure hardens the epoxy.

76. On a separate floor, to prevent particle contamination, the bonded wafers and windows will be sawed. A metal frame contains the wafers, which have been placed on sticky dicing tape. The saw cuts or dices in between and along the edges of the die, and singulates the bonded wafers into individual die.

77. Back in the clean room, epoxy is dispensed inside the package cavities of a header. A computer selects only the good CMOS die. They are picked off the tape and placed into the cavities.

78. The devices are again baked.

79. At the bonding station, a thin gold wire is used to bond the device pads to the frame's wire leads. The mirrors can now be electrically and optically tested for the first time.

Chapter 8 – Tests

80. Voltage to the CMOS actuation pads attracts the mirrors and flips them ON and OFF, to ensure that they are all moving and functioning. The good chips move on to encapsulation.

81. A black epoxy is spread around the mirrors to hide any structures, like the gold wires that might scatter or reflect light, which would reduce the image contrast.

82. The devices are then baked to harden the epoxy.

83. In these burn-in furnaces the mirrors are electrically tested. For two to twenty four hours the mirrors flip back and forth continuously. The screen shows the checkered pattern of the pixels as they flip.

84. To overcome stiction, the tendency for surface forces to cause small structures to stick, the mirrors rely on the restoring force of the torsion hinge to return to a FLAT, ON or OFF state.

85. Looking closely at the yoke we also find small spring tips. These tips deflect slightly as they land on the lower surface. When released, the stored potential energy provides a slight kick that helps overcome adhesive forces.

86. After Burn-In, a tester measures whether or not the mirrors tilt.

87. A second tester checks the mirror movement by applying various voltages and measuring the responses. These movements can vary between devices with different angles and mirror sizes.

88. The final test is a visual test. The image is projected using different colored screens and inspected to ensure there are no defects. A defect projected on a black screen, for example may not show on a dark background but will show when projected against a white background.

89. Here we see a test device, which has been programmed with specific images. The mirrors reflect the image in black and white. These same images, reflected from the DLP device, go through a series of lenses and color filters to be projected in color.

90. A laser brands the appropriate information on the back of the DLP devices before they are shipped to the suppliers around the world. They in turn produce the many projectors we use on a daily basis.

DESIGN (Sensors)

Chapter 9 – MEMS Design Process

91. To see how sensors are designed let's go to Freescale Semiconductor. Designing MEMS devices is a critical part of manufacturing and a team effort. Experts bring together the mechanical and electrical design and manufacturing aspects to create complete micro systems in different fields.

92. Two of the most common types of sensors monitor pressure and movement.

93. Pressure sensors measure pressure change in gases and liquids. In most cases a thin silicon membrane responds to a change in pressure and triggers a response. This requires an opening in the package to keep one side of the membrane exposed to the environment. In cars they monitor things like combustion pressure to improve fuel efficiency and side crash detection. These sensors monitor the air pressure of tires. These monitor blood pressure.

94. Inertial Sensors measure a change in movement. They include accelerometers and gyroscopes.

95. Accelerometers measure linear movement along the x, y, and z-axes. They detect acceleration, which is a change in speed or direction. They are used in cars for safety critical applications to improve dynamic control. In this electric car they deploy airbags while pressure sensors monitor tire pressure.

96. Accelerometers are found in a variety of motion detection consumer products. In sports like golf they provide information to help improve one's swing.

97. Gyroscopes measure rotational movement known as yaw, roll, and pitch. These gyros are used in cars. When they sense a car has lost control and begins to roll they deploy a side airbag.

98. The design of sensors and MEMS in general, is done in an iterative top down workflow that requires revisions and feedback.

99. This process typically begins when the customer presents requirements to a team of mechanical, electrical, and systems engineers, as well as marketing and sales experts.

100. The project requirements are then presented to the design team who scope the project and establish a roadmap.

Chapter 10 – Design Team

101. Let's take a look at the project from the different perspectives of the designers who are working on it. The mechanical designer determines the limitations of the mechanical transducers. This is the part that converts motion into a change in electrical signal such as capacitance. This signal is read by the electrical, or Application Specific Integrated Circuit, known as ASIC. With accelerometers, an abrupt motion or acceleration moves the proof mass. Each sense electrode, connected to runners, collect the change in capacitance signal. The runners, connected to electrical leads, carry the signal to the ASIC.

102. The ASIC designer checks that the change in capacitance, which is converted to a voltage, meets the circuit’s requirements.

103. The systems engineer creates an architectural level design and writes the specifications. These specifications can include the level of integration or layout of the device.

104. With system-in-package a sensing cell measures the force of acceleration, which results in changing capacitance. Freescale’s IC design converts capacitance to voltage and allows the sensor to be calibrated or checked for accuracy. This particular sensor is used in the game Guitar Hero.

105. Some sensors bond the die in a stack formation to reduce the footprint. Here we see the pressure sensor. On the other side we see three devices: the micro controller, radio frequency transmitter, and a dual axes accelerometer. These stack devices can track the motion in golf swings. In cars, they monitor sensors without using wires.

106. After scoping, partitioning and model generation is the next phase. Here, the Microsystems Group partitions the components of the system into blocks that represent the physics of the mechanical and electrical chips.

107. Each block has a mathematical representation that consists of lines of equations, or code. The design often starts with a few lines of code. More lines are added to enhance the model's details and set the operational parameters.

108. The transducer model allows designers to predict proof mass motion. They do this by applying different accelerations to the model. The calculations they use address issues like mass and stiffness of the proof mass and the change in capacitance.

109. Other equations determine electrostatic attraction and internal gas resistance that dampens the motion.

110. The package model determines the effect of the packaging, including stress, on the performance of the MEMS chip. The result is a transducer systems block that predicts the changes in capacitance. These changes will be monitored by the ASIC logic chip.

111. The ASIC designer works on the conversion of capacitance to voltage. The voltage is then sampled and converted to a digital signal. The designer then applies final digital algorithms. Some of these will be used to set up the conditions for the final testing.

112. Once the System Engineer feels comfortable with the partitioning and modeling of the MEMS and ASIC designs, the work progresses to the analysis phase.

113. Here, the Systems Designer brings the two together to find out how they work. MEMS and ASIC blocks simulate performance and ensure the results meet product specifications. While the design needs to be represented in a mathematical format, it also now needs to include the impact of fabrication.

114. With surface micromachining, deposition, photolithography and etch produce feature sizes that may not exactly match the design. The designers need to know how the process works.

115. For example, a deep reactive ion etch, known as the Bosch Process, creates deep straight etched walls by alternating chemicals used in the etch chamber. These high aspect ratio structures increase the surface area of the sense elements vertically. As a result, the chips will need fewer elements and can therefore be made smaller.

116. Designers make adjustments and data moves up and down the process flow two to five times or more. Models run over and over again as areas are repartitioned or variations tightened. Before the process finishes, the final data is checked against the design specifications again.

117. In verification, the systems engineer receives and checks analysis data. The mechanical designers verify their MEMS design with layout 2D CAD tools. And circuit designers execute and verify with transistor level schematics.

118. Once cleared, the mechanical and electrical designers create their final designs, known as “tape out.” The project then moves to fabrication.

Chapter 11 – Conclusion & Credits

119. There are many types of MEMS devices. Biochemical microarrays, printed with stacks of specific peptide sequences and used in DNA studies, can quickly identify the existence of cancer.

Tiny cantilevers, or probes, used in the Atomic Force Microscope map the surface of atomic structures. MEMS serve as a bridge between the micro world and the even smaller nano world.

120. As technology moves forward the potential of MEMS devices is vast and limited only by our own mechanical ingenuity.