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Institut für Integrierte Systeme
Integrated Systems Laboratory

Department of Information Technology and Electrical Engineering

VLSI III: Test and Fabrication of VLSI Circuits

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Exercise 2

Wafer-Stage IC Probing and Characterization

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Reminder:
With the execution of this training you declare that you understand and accept the regulations about using CAE/CAD software installations at the ETH Zurich. These regulations can be read anytime at `http://eda.ee.ethz.ch/index.php/Regulations`.

1 Introduction

In this training, you will acquire hands-on experience with wafer-handling, IC probing, device characterization equipment, and with LASER-trimming (optional). This training will be held in the physical characterization laboratory located in ETZ H 76.

The learning goals of this training are:

- Learn what IC probing is and understand its importance in IC fabrication.
- Learn how to manipulate a wafer probing station for visually examination and probing of ICs.
- Learn how to use a parameter analyzer for electrical characterization of semiconductor devices.
- Learn how to use a LASER-cutter to repair IC structures or trim integrated passive elements.

2 Preparations

To prepare for this exercise, please read the section about chip packaging and wafer sorting in H. Kaeslin, *Top-down Digital VLSI Design: From Gate-Level Circuits to CMOS Fabrication*, Section 12.4; as well as the section about the basic MOS transistor models (refer to H. Kaeslin, *Top-down Digital VLSI Design: From Gate-Level Circuits to CMOS Fabrication*, Section 9.7.2.

We will use the Karl Suss PSM 6 submicron prober, a HP 4156A semiconductor parameter analyzer, and an Alessi LG2 LASER cutter system with XY aperture control ECL-06. You can find detailed manuals in a specially prepared folder next to the probing station.

3 Prober Handling

CAUTION:

MAKE SURE THAT THE PROBER NEEDLES DO NOT TOUCH EACH OTHER OR ANY OTHER OBJECTS DURING THE HANDLING OF THE PROBER (OF COURSE, THEY ARE ALLOWED TO TOUCH THE APPROPRIATE CONTACTS ON THE WAFER). THERE IS ALMOST ZERO MARGIN FOR THAT KIND OF MISHAP AS THE NEEDLES ARE VERY EASILY BENT, WHICH MAKES THEM NO LONGER USABLE FOR PROBING. BE EXTRA CAREFUL WHEN DIALING BETWEEN MICROSCOPE OBJECTIVES.

MAKE SURE THE SMALLEST MICROSCOPE OBJECTIVE IS DIALED-IN, AND THE MICROSCOPE MANIPULATOR IS IN THE MIDDLE POSITION, WHENEVER YOU MOUNT OR UNMOUNT A WAFER.

3.1 Wafer Mounting and Visual Examination

IC probing is performed on the bare wafers and unpackaged dies, which is why this task is usually done in a cleanroom environment where the contamination with particles (dust, hair, skin flakes, liquids, etc.) is kept at a minimum. We will handle the wafers and probing station in an unconditioned laboratory environment; thus, you will see a lot of contaminants on the wafer surface that would not usually be there.

Student Task 1:

- Push the *Load* button on the prober remote control to lower the wafer chuck.
- Release the wafer stage lock by pushing the *Stop* button (the corresponding LED must be turned off) such that the stage can be moved freely on the granite plate, and be sure the Y-axis break is released (the *X-only* LED must be turned off). Now, pull the stage from underneath the microscope to full forward position, and lock it in place by pushing *Stop*.
- Open the wafer carrier box, carefully grab wafer No. #2 (BIC 33) at its straight side with the wafer tweezers. Position your other hand below the wafer WITHOUT TOUCHING IT, just for the case that you lose your hold of it, and pull it carefully from the carrier. If you are a group of two people, one can hold the carrier box, while the other one pulls the wafer out of it.
- Position the wafer flat onto the wafer chuck and hold it firmly there with the tweezers until you have engaged the vacuum by pushing the *Vac* button on the remote (the LED must be on). The wafer should be positioned on the chuck such that the IC lines are as orthogonal as possible to the x and y axis of the probing station. For small rotational corrections the Theta micrometer screw (the big knurled screw on the wafer chuck) can be used without removing the wafer from the chuck. If the wafer orientation requires a larger adjustment, grab the wafer with the tweezers, switch off the vacuum, reposition the wafer and re-engage the vacuum. If necessary adjust the chuck vacuum track thumbscrews as necessary according to the size of the wafer.
- Once the wafer is positioned correctly, release the stage lock once again, slide the wafer chuck back, center it under the microscope, and fix the stage with *Stop*. Then, push the *Load* button to bring the wafer up into working position.
- Use the microscope to examine the surface and the IC structures on the wafer. Start with the smallest objective lens, and focus a structure on the wafer. You can then try different objective lenses and play around with the intensity of the illumination to focus the various metal layers and semiconductor structures. This wafer contains instances of a test chip containing arrays of different semiconductor test structures including diodes, resistors, capacitors, bipolar and MOS transistors, and also optical patterns.

3.2 Contacting a MOSFET with the Prober Needles

Student Task 2:

- Use the microscope with the smallest objective and the 2x zoom (small dial on the right of the microscope) to find the test sets No. 1906 to No. 1910 in one of the chips. Those are NMOS transistors of different sizes, each one of them has four pads around it connecting to its four terminals.
- Now, we will use the four PH 150 submicron probe heads equipped with tungsten needles to make contact with each one of the four terminals of one transistor; again, be very, very careful not to damage the needles when moving the probe heads around! If you are a group of two people, each one of you may contact two of the terminals to speed up the exercise a little.
- First, choose one of the NMOS transistors to contact, and center the microscope on it. The ones with black dots or scratches on their pads have been used in previous exercise sessions; select one that has clean pads. Make sure the wafer stage is locked (the *Stop* LED is on).
- Carefully move the probe head with its needle closest to you over the appropriate pad (either the lower left or lower right one). Use both hands to better control where the head and the needle is moving, and push the lever on the side of the probe head to temporarily release the vacuum that holds it in place on the semiring. You might have to adjust the height of the needle using the Z-axis micrometer screw on the head to avoid bumping into the wafer or scratching across its surface. Also, make sure you do not touch the objective lens with the needles. The position is correct, if you see the needle appearing as a back shadow close to the pad through the microscope, and if the needle tip is roughly over the corner of the pad farthest away from the transistor.
- BE EXTREMELY CAREFUL NOT TO BUNCH THE NEEDLES INTO EACH OTHER when you position the other three probes in the same way over their respective pad. The easiest and safest way to do it is to first use the smallest objective with the 2x zoom to roughly position the needles near the pad but not too close to the other needles, and then adjust the position using the X and Y axis micrometer screws on the head to close-in on the pad.
- Only then, use the larger objective to touch down with the needles on the pad. If you do not see the shadow of the needle even though it is close enough to the pad, it is still too far up. The needle has a firm contact with the pad, if it leaves a black scratchy trace when you move the Z-axis screw a tiny little back and forth.

4 Characterizing a MOSFET

In the previous task, you have established an electrical connection between the four terminals of an integrated MOSFET and the prober needles that themselves are connected to the measurement channels of a HP 4156A semiconductor parameter analyzer. With this setup we can fully characterize the MOSFET, and, e.g., find its threshold voltage, or measure and plot its I_D vs. V_{DS} curve for different biasing voltages. You will not have enough time in this exercise session to do both of them. Therefore, you are free to choose which one of the two characteristics you want to measure, and correspondingly either skip Section 4.1 or Section 4.2.

4.1 Measuring the threshold voltage

Measuring the threshold voltage V_{TH} of a MOSFET can be done in many different ways.[1] One of the simplest is the extrapolation method in the saturation region. The drain current in saturation is

$$I_D = \frac{W}{L}\frac{\mu C_{ox}}{2}(V_{GS} - V_{TH})^2.$$

The threshold voltage is determined by plotting $\sqrt{I_D}$ versus V_{GS} and extrapolating the curve to zero drain current. Since I_D is dependent on mobility degradation and series resistance, the extrapolation is done at the point of maximum slope, i.e., where the derivative $\frac{\partial I_D}{\partial V_{GS}}$ has its maximum. Setting $V_{DS} = V_{GS}$ ensures that the MOSFET is is saturation for all values of V_{GS}.

Student Task 3: Use the HP 4156A semiconductor parameter analyzer to evaluate the threshold voltage of the probed NMOS transistor:

- Switch on the HP 4156A, and while it is starting up, draw the schematic symbol of an NMOS transistor with four terminals and write down which probe is connected to which terminal. Use the numbers indicated on the BNC cables connecting the probe heads to the HP 4156A. They correspond to the channel number assigned to the corresponding probe in the analyzer.
- Make the following definitions in the *Channels: Channel Definition* screen:

  Measure Mode: Sweep

  Channels:

UNIT	VNAME	INAME	MODE	FCTN	STBY
SMU1:HR	VG	IG	V	VAR1'	
SMU2:HR	VS	IS	COMMON	CONST	
SMU3:HR	VB	IB	COMMON	CONST	
SMU4:HR	VD	ID	V	VAR1	

  Leave the rest of the table as it is. Note the difference between VAR1' (with apostrophe) assigned to VG and VAR1 (without apostrophe) assigned to VD.
- Make the following definitions in the *Channels: User Function Definition* screen:

  User Function:

NAME	UNIT	DEFINITION
SQID	A	SQRT(ID)
DSQID	A	DIFF(SQID,VG)

[1] see, e.g., Ortiz-Conde et al.: *"A review of recent MOSFET threshold voltage extraction methods,"* Microelectronics Reliability, vol. 42, no. 4, pp. 53–596, Elsevier, 2002

- Make the following definitions in the *Measure: Sweep Setup* screen:

Variable:

	VAR 1	VAR 2
UNIT	SMU4:HR	
NAME	VD	
SWEEP MODE	SINGLE	
LIN/LOG	LINEAR	
START	0.0000 V	
STOP	3.0000 V	
STEP	10.0mV	
NO OF STEP	301	
COMPLIANCE	100.00mA	
POWER COMP	OFF	

	VAR1’
UNIT	SMU1:HR
NAME	VG
OFFSET	0.0000 V
RATIO	1.000
COMPLIANCE	100.00mA
POWER COMP	OFF

The rest of the settings is OK.

- Make the following definitions in the *Display: Display Setup* screen:

Display Mode: Graphics

Graphics:

	Xaxis	Y1axis	Y2axis
NAME	VG	SQID	DSQID
SCALE	LINEAR	LINEAR	LINEAR
MIN	0.000000000 V	0.000000000 A	0.000000000 A
MAX	3.000000 V	100.0000000 mA	100.0000000 mA

The rest of the settings is OK.

- Execute the measurement by pushing the *Single* button on the front panel of the HP 4156A.

  Is the plot what you expect?

  If not, refer to the debug checklist in Section 4.3

- Find the threshold voltage. For that, bring up the *Graph/List Graphics* screen if it is not already being displayed, and switch the *Axis* option at the bottom of the screen to *Y2*. Select the *Marker/Cursor* option at the bottom of the screen, and switch the *Marker* option at the right edge of the screen to *On*. Then, select the *Marker Min/Max* option on the right edge of the screen, which will put one marker at the maximum on the Y2 curve and one at the same x-axis value on the Y1 curve. Next, switch the *Axis* option at the bottom of the screen to *Y1*, select the *Line* option at the bottom of the screen, switch the *Line Select* option at the right edge of the screen to *1*, and switch the *Tangent* option at the right edge of the screen to *On*. Finally, switch the *Line* option at the right edge of the screen to *On*, and the threshold voltage is displayed at the bottom of the plot as intercept point with the VG axis (it should not be too far from 900mV, depending on the device you chose).

4.2 Measuring the I-V characteristic

This measurement will report the drain current I_D as a function of the drain-source voltage V_{DS} of an NMOS transistor for different gate-source voltages. This characteristic allows a circuit designer to determine the correct operating point for this NFET according to the task and the performance he or she likes the circuit to achieve.

Student Task 4: Use the HP 4156A semiconductor parameter analyzer to plot the characteristic I-V curves of the probed NMOS transistor:

- Switch on the HP 4156A, and while it is starting up, draw the schematic symbol of an NMOS transistor with four terminals and write down which probe is connected to which terminal. Use the numbers indicated on the BNC cables connecting the probe heads to the HP 4156A. They correspond to the channel number assigned to the corresponding probe in the analyzer.
- Make the following definitions in the *Channel Definition* screen:

  Measure Mode: Sweep

  Channels:

UNIT	VNAME	INAME	MODE	FCTN	STBY
SMU1:HR	VG	IG	V	VAR2	
SMU2:HR	VS	IS	COMMON	CONST	
SMU3:HR	VB	IB	COMMON	CONST	
SMU4:HR	VD	ID	V	VAR1	

  Leave the rest of the table as it is.
- Make the following definitions in the *Measure: Sweep Setup* screen:

  Note that, while in the definition of variable 1, you can simply set the start, the stop and the step size (the number of steps is calculated automatically), in the definition of variable 2, you must specify the start, the step size and the number of steps (and the stop is calculated automatically).

  Variable:

	VAR 1	VAR 2
UNIT	SMU4:HR	SMU1:HR
NAME	VD	VG
SWEEP MODE	SINGLE	SINGLE
LIN/LOG	LINEAR	LINEAR
START	0.0000 V	0.0000 V
STOP	5.0000 V	3.5000 V
STEP	200.0mV	250.0mV
NO OF STEP	26	15
COMPLIANCE	100.00mA	100.00mA
POWER COMP	OFF	OFF

  The rest of the settings is OK.

- Make the following definitions in the *Display: Display Setup* screen:

  Display Mode: Graphics

  Graphics:

	Xaxis	Y1axis	Y2axis
NAME	VD	ID	
SCALE	LINEAR	LINEAR	
MIN	0.000000000 V	0.000000000 A	
MAX	5.000000 V	3.0000000 mA	

  The rest of the settings is OK.

- Execute the measurement by pushing the *Single* button on the front panel of the HP 4156A.

  Is the plot what you expect?

  If not, refer to the debug checklist in Section 4.3

4.3 Debug Checklist

You can skip this paragraph, if the measurements from the previous section were successful. If the results of your measurement are not what you expect, go through the following list to find the possible cause. The items are ordered in terms of likeliness of being the cause of the issues your having.

1. Be sure that what you expect to see as outcome of your measurement makes sens from a theoretical point of view.
2. In the *Graph/List* screen of the HP 4156A, select the *Scaling* option at the bottom of the screen, and the *Autoscaling* option at the right edge of the screen.
3. Check whether the channel numbers correspond to the correct terminals of the NMOS, and whether the channel definitions are correct.
4. Check your settings in the user function (only for the V_{TH} measurement), measurement, and display screens of the HP 4156A.
5. Check whether the probe needles have good contact with the pads and whether all the cables are connected correctly.
6. Probe another NMOS. In case the needles are still connected to the current NMOS, this task is very simple: You only have to turn the platen control knob (the big turning knob to your left on the base of the prober station) in the direction indicated with “Sep.” to lower the wafer chuck together with the granite plate it sits on. Using the Y-axis adjustment micrometer screw (right in front of the wafer chuck) you can translate the wafer until the needles are positioned over the pads of the new NMOS device. Then, you can turn the platen control knob in the direction indicated with “Cont.” back to its original position, which lifts the wafer up against the needles and established the contact between the needles and the pads. Now, you understand why it is important to have the wafer aligned to the x and y axis of the prober, and why the test structures have been layed-out in orthogonal arrays preserving the same pad geometry.
7. If after probing another NMOS the results are still not what you expect, go through the list again, as you might have missed something.

5 LASER-trimming (optional)

While the ratio of passive components (such as resistors and capacitors) are usually very accurate (< 1% mismatch) in CMOS processes, their absolute values are not (up to ≈ 30% standard deviation is not unusual), mostly due to process variations. If a resistor or capacitor is required to be more precise, its value can be adjusted after fabrication by LASER-trimming. Since LASER-trimming can only remove material but not add any, resistors to be trimmed must be fabricated with a lower resistance than the target value, whereas capacitors are fabricated with a higher value.

CAUTION:

LASER RADIATION IS HARMFUL FOR YOUR EYES AND MAY DAMAGE YOUR SIGHT PERMANENTLY IF YOU DO NOT ADHERE TO THE FOLLOWING RULES:.

DO NOT LOOK DIRECTLY INTO THE LASER BEAM OR THROUGH THE BINOCULARS OF THE MICROSCOPE WHENEVER THE LASER IS ARMED.

REFLECTED LASER LIGHT CAN BE AS HARMFUL AS DIRECT RADIATION. DO NOT LOOK ONTO THE WAFER SURFACE WHENEVER THE LASER IS ARMED.

DO NOT USE THE LASER WITHOUT THE EXPLICIT PERMISSION FROM THE SUPERVISING ASSISTANT TO ACTIVATE THE LASER.

MAKE SURE THE BUTTON ACTIVATING THE LASER CANNOT BE PUSHED ACCIDENTALLY.

TURN OFF THE LASER DRIVER ALESSI LG2 AND CLOSE THE LASER PROTECTIVE SHUTTER ON THE ALESSI LASER WHEN YOUR ARE DONE USING IT.

WHEN USING THE LASER, START AT THE LOWEST POSSIBLE POWER SETTING AND INCREASE THE POWER ONLY AS HIGH AS NECESSARY TO ACHIEVE THE DESIRED EFFECT ON THE WAFER.

Student Task 5: Now, we want to remove some of the metal connecting the drain of the MOSFET transistor and the pad.

- Make sure the LASER protective shutter is closed. Dial the *Power Level* on the LG2 to its lowest setting. Dial the *Pointer* to its highest value, and make sure the lever underneath the pointer dial is switched to *continuous*. Turn the key into the *On* position, and push the *Enable* button to start the LASER driver. An acoustic signal will be issued to warning you that the LASER is now armed. CAUTION: THE LASER IS NOW ARMED, and both the *Trigger* lever on the LG2 and the remote activation button will activate the LASER.
- Open the LASER protective shutter. Now, you should be able to see the red LASER pointer that shows you the size and the location where the working LASER will hit the wafer.
- Adjust the aperture size on the ECL-06 device. Depending on the selected microscope objective and the focus setting the LASER site will have a different form.
- Lets try to change the width of the NMOS transistor by cutting its gate in half. But, before we start LASER-ing away anything, think about how the MOSFET characteristic you measured in the previous task will change with the trimming. Draw a quick sketch of what the characteristic curve will look like after trimming.

- If the LASER spot has the correct shape and the focus is in the right place, you can push the button to activate the LASER. The LASER will fire once for each time you push the button. Push it just once to start with, and check your result visually on the screen or through the microscope (CLOSE THE LASER PROTECTIVE SHUTTER FIRST!).
- Repeat the measurement of the MOSFET characteristic by pushing the *Append* button on the HP 4156A.

  Did it change as expected?

  If not, you may try to change the parameters of the LASER trimming by adjusting the LASER spot size, position, focus, and power level.
  BE CAREFUL WHEN YOU DIAL-IN THE LARGEST OBJECTIVE LENS AS IT MAY TOUCH THE PROBE ARMS AND DAMAGE BOTH THE NEEDLES AND THE WAFER.
- If you are satisfied with the result, you can close the laser protective shutter, and switch off the LASER driver by pushing the *Enable* button and turn the key to the *Off* position.

6 Unmounting the Wafer and Cleaning up

Student Task 6:

- Make sure that the LASER is switched off and that the LASER protective shutter on the microscope is closed.
- Dial-in the smallest objective lens.
- Carefully lift all probe needles up from the wafer and slide the probe heads back to the rear of the probe station. Be extra careful not to have the needles touch each other or any other object.
- Unmount the wafer from the prober station by going through the following procedure: First, dial-back to the smallest microscope objective and push the *Load* button to lower the wafer chuck. Release the stage lock (*Stop* button), pull the wafer chuck to full forward position, and re-engage the stage lock. Then, grab the wafer with the tweezers. Make sure you have a firm hold of the wafer, disengage the vacuum, and again help each other inserting the wafer carefully back into its original position in the wafer carrier.
- Switch off the parameter analyzer, and then cut the power to the prober station by throwing the main switch on the power distributor below the probe station.

7 Discussion

After having completed this exercise, you should be able to answer the following questions:

- Why is IC probing necessary and what is the difference between IC probing and chip testing?
- What is a probe card, and why did we not use one to measure the MOSFET in this exercise.
- Why is there a need to characterize semiconductor structures on the wafer?
- What is LASER-trimming and in what cases is it useful/required?