FINAL SCRIPT: APPROVED FOR FILMING

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Title: Using Laser Scanning Microscopy to Determine Electromigration in Molybdenum Disilicide

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Author Questionnaire

1. **Microscopy**: Does your protocol require the use of a dissecting or stereomicroscope for performing a complex dissection, microinjection technique, or something similar? **No**

2. **Software:** Does the part of your protocol being filmed include step-by-step descriptions of software usage? **Yes, all done**

3. **Filming location:** Will the filming need to take place in multiple locations? **No**

Current Protocol Length
Number of Steps: 25
Number of Shots: 56 (45 SC)

Introduction

Videographer: Obtain headshots for all authors available at the filming location.

1.1. **Julia Baldauf:** The scope of the research is determining the influencing factors of electromigration phenomena in molybdenum disilicide. Such as the influence of the length of lines under test and the influence of encapsulating materials on the effective charge and the apparent activation energy **[1]**.

1.1.1. INTERVIEW: Named talent says the statement above in an interview-style shot, looking slightly off-camera. *Suggested B-roll:* 2.4.1

What are the current experimental challenges?

1.2. **Julia Baldauf:** The current experimental challenges lie in expanding this method to higher temperatures **[1]**.

1.2.1. INTERVIEW: Named talent says the statement above in an interview-style shot, looking slightly off-camera.

What advantage does your protocol offer compared to other techniques?

1.3. **Julia Baldauf:** The method shown in this study uses a laser scanning microscope instead of a scanning electron microscope. This removes the need of the sample preparation. Our method does not need elaborate SEM preparation and is faster compared to measurements in the SEM **[1]**.

1.3.1. INTERVIEW: Named talent says the statement above in an interview-style shot, looking slightly off-camera. *Suggested B-roll:* 2.6.1

What research questions will your laboratory focus on in the future?

1.4. **Julia Baldauf:** Our research lab will focus on determining the effective ion charge and activation energy of molybdenum disilicide for elevated temperatures and molybdenum disilicide implanted with different dopant species. We will also use this method for the observation of artificially generated voids in molybdenum disilicide and other materials **[1]**.

1.4.1. INTERVIEW: Named talent says the statement above in an interview-style shot, looking slightly off-camera. *Suggested B-roll:* 2.2.2

Videographer: Obtain headshots for all authors available at the filming location.

Testimonial Questions (OPTIONAL):

Videographer: Please ensure that all testimonial shots are captured in a wide-angle format, while also maintaining sufficient headspace, given that the final videos will be rendered in a 1:1 aspect ratio.

Can you share a specific success story or benefit you've experienced—or expect to experience—after using or publishing with JoVE?

1.5. **Julia Baldauf:** We expect a reduction in training time~~,~~ and an increase of collaborations with industrial and academic partners **[1]**.~~, and an increase of citations after publishing with JoVE.~~

1.5.1. INTERVIEW: Named talent says the statement above in an interview-style shot, looking slightly off-camera. *Suggested B-roll:* 2.2.2

Protocol

2. Determination of the Electromigrated Volume

Demonstrator: Julia Baldauf

2.1. To begin, switch on the laser scanning microscope and open the measurement and analytics software **[1]**. Using an appropriate sample holder, secure the sample so it remains fixed on the microscope stage during scanning **[2]**.

2.1.1. WIDE: Talent switching on the laser scanning microscope and launching the software.

2.1.2. Talent placing the sample in the holder.

2.2. Prepare an accurate current source and necessary wires for electrical connection **[1]** and adjust the height of the microscope stage **[2]**.

2.2.1. Talent gathering the current source and wires.

2.2.2. Talent adjusting the microscope stage height.

2.3. Now, position the sample in the sample holder under the laser scanning microscope **[1]**. Align the sample parallel to the table of the microscope and fix it in place to prevent any movement during measurements **[2]**.

2.3.1. ~~Talent placing the sample in the holder under the microscope~~. Talent moves the sample under the sample holder to put the region of interest into focus. NOTE: Shot modified, but VO does not need to change. Videographer's NOTE: Added a close-up shot

2.3.2. Talent aligning and securing the sample to the microscope stage.

2.4. Connect the electrical outlet of the current source to the sample or sample holder based on the setup **[1]**. Confirm that the bond wires are still attached to the sample by optical inspection **[2-TXT]**.

2.4.1. Talent connecting the current source wires to the sample.

2.4.2. Talent inspecting bond wires via low current or optical inspection. **TXT: Alternatively, apply a low current briefly to check the connections**

2.5. Adjust the height difference between the objective lens and the sample to bring the

region of interest into focus using the lowest magnification objective lens **[1]**. Use manual focus or click **Auto focus** in the **Observe** window of the measurement software **[2]**.

2.5.1. Talent ~~adjusting~~ fine-tuning the adjustment of the objective lens to bring the region of interest of the sample into focus. NOTE: Shot slightly modified, but VO does not need to change. Videographer's NOTE: Added a close-up shot

2.5.2. SCREEN: 68158_screenshot_1.mp4 00:19-00:38.

2.6. Change the objective lens to a higher magnification and refocus on the region of interest **[1]**. Continue this process until the region of interest is clearly visible at the highest magnification, such as 150x, in the **Observe** window **[2]**. Set **Tools Measure** and **Average count** to 4 **[3]**.

2.6.1. Talent switching objective lenses. Author's NOTE: The video starts with the object of the lowest magnification, focusing on the region of interest, and then changes to an objective with a higher magnification and refocusing until the region of interest is in focus using the objective with the highest magnification available.

2.6.2. SCREEN: 68158_screenshot_1.mp4 01:30-01:41.

2.6.3. SCREEN: 68158_screenshot_1.mp4 01:41-01:46.

2.7. Then, click **Options** followed by **Auto save**, select a save destination folder, enter a file name prefix and sample, and click **Ok [1]**. Open the **Measure** window, select **Expert Mode**, and choose **Measurement settings** followed by **Surface profile, Super fine (2048 x 1536)** *(twenty-forty eight by fifteen thirty six),* and **High-accuracy [2]**.

2.7.1. SCREEN: 68158_screenshot_1.mp4 01:46-01:59.

2.7.2. SCREEN: 68158_screenshot_1.mp4 01:59-02:18.

2.8. To increase the distance between the objective lens and the sample, click the upward arrows until the entire surface appears black in the window, then click **Set upper pos [1]**. Next, decrease the distance using downward arrows until the full surface is visible, and continue until the surface turns black again, then click **Set lower pos [2]**.

2.8.1. SCREEN: 68158_screenshot_1.mp4 02:18-02:32.

2.8.2. SCREEN: 68158_screenshot_1.mp4 02:32-02:38.

2.9. Click **Auto gain** and then **Start measurement** to begin scanning the surface **[1]**. Increase the distance between the objective and sample by several millimeters up to 1

centimeter using the upward arrows to defocus the laser before stressing the sample **[2]**.

2.9.1. SCREEN: 68158_screenshot_1.mp4 02:38-02:52.

2.9.2. SCREEN: 68158_screenshot_1.mp4 04:50-05:08.

2.10. Apply current stress using the predetermined conditions, such as current density and time, then stop the current flow after the specified time **[1]**.

2.10.1. SCREEN: 68158_screenshot_1.mp4 05:05-05:10 and 12:19-12:23.

2.11. 3 to 5 minutes after applying current stress, focus the laser scanning microscope on the region of interest when the sample returns to room temperature **[1]**.

2.11.1. SCREEN: 68158_screenshot_2.mp4 00:24-00:28 and 00:50-00:55.

2.12. Continue focusing until the sample no longer shifts its focus on its own to ensure there are no drifts in surface measurement due to temperature changes **[1]**.

2.12.1. SCREEN: 68158_screenshot_3.mp4 00:03-00:20.

2.13. Scan the same region that was scanned before the current stressing using the exact same settings as used earlier **[1]**.

2.13.1. ~~Talent performing a repeat scan using previously defined settings.~~ SCREEN: 68158_screenshot_3 00:20-02:32 *Video editor: Speed up the video*

2.14. Open the analytics software and click **File** and **Open**, then locate the correct file **[1]**. If the file is already open, proceed to correct the tilt of the samples after selecting **Process image** and **Correct tilt** to launch the tilt correction window **[2]**.

2.14.1. SCREEN: 68158_screenshot_4_R1.mp4 00:02-00:10.

2.14.2. SCREEN: 68158_screenshot_4_R1.mp4 00:10-00:13.

2.15. In the correction window, set the display image to **Laser+Optical** *(laser plus optical)* and choose the correction method **Plane tilt (3 points)** *(plane tilt 3 points)* to display three points on the image **[1]**. Move the guiding lines so that most of each line lies in the background **[2]** and adjust the three points close to the region of interest **[3]**.

2.15.1. SCREEN: 68158_screenshot_4_R1.mp4 00:13-00:17.

2.15.2. SCREEN: 68158_screenshot_4_R1.mp4 00:17-00:20.

2.15.3. SCREEN: 68158_screenshot_4_R1.mp4 00:20-00:22.

2.16. Next, move the three points so that the plane represented by two straight lines in the cross sections aligns with the background **[1]**. Select **Do not adjust offset height 0 data** and **Auto adjust height range**, then click **Execute,** followed by **Close** to apply the corrections **[2]**.

2.16.1. SCREEN: 68158_screenshot_4_R1.mp4 00:22-00:24.

2.16.2. SCREEN: 68158_screenshot_4_R1.mp4 00:24-00:29.

2.17. To open the trimming window, click **Process image** and **Trimming [1]**. Choose the trimming width and height according to the region of interest and adjust the selection rectangle to encompass the entire region of interest **[2]**. Save the corrected and trimmed image **[3],** and click **File,** and locate the correct file **[4]**.

2.17.1. SCREEN: 68158_screenshot_4_R1.mp4 00:37-00:39.

2.17.2. SCREEN: 68158_screenshot_4_R1.mp4 00:39-00:47.

2.17.3. SCREEN: 68158_screenshot_4_R1.mp4 00:47-00:54.

2.17.4. SCREEN: 68158_screenshot_4_R1.mp4 00:57-01:02.

2.18. To export the region of interest while preserving three-dimensional information, click **File,** followed by **Output 3D-CAD data** to open the output parameter window **[1]**. Set **Skip amount** to 1, **Actual number display accuracy** to 10, **XY zoom ratio** to x1, and **Enhance height** to 100 percent **[2]**.

2.18.1. SCREEN: 68158_screenshot_4_R1.mp4 01:02-01:06.

2.18.2. SCREEN: 68158_screenshot_4_R1.mp4 01:06-01:10.

2.19. Then, choose **Surface [1]** and click **Set** to confirm the settings **[2]**. Select the **Point group data** to save uniquely labeled data **[3]**. After the export is completed, a confirmation window will appear **[4]**.

2.19.1. SCREEN: 68158_screenshot_4_R1.mp4 01:10-01:11.

2.19.2. SCREEN: 68158_screenshot_4_R1.mp4 01:11-01:11.

2.19.3. SCREEN: 68158_screenshot_4_R1.mp4 01:11-01:20.

2.19.4. SCREEN: 68158_screenshot_4_R1.mp4 01:20-01:22.

2.20. Open the version of the evaluation software and packages **[1]**. To start the program, click the arrow icon **[2].** Navigate to the folder containing the ASC files after clicking **Open** and selecting the appropriate save path **[3]**. Load the ASC files into the program with the correct sample name from the selection list **[4]**. Ensure the **Area** option is selected, then click **Cross** followed by **Area [5]**.

2.20.1. SCREEN: 68158_screenshot_6.mp4 00:01-00:11.

2.20.2. SCREEN: 68158_screenshot_6.mp4 00:11-00:14.

2.20.3. SCREEN: 68158_screenshot_6.mp4 00:14-00:16.

2.20.4. SCREEN: 68158_screenshot_6.mp4 00:16-00:20.

2.20.5. SCREEN: 68158_screenshot_6 00:20-00:30.

2.21. Using the mouse, select a rectangle on the substrate surface to define the scale for height **[1]**. Examine the two height histograms before and after the current stressing, positioned beside the region of interest image, and adjust the selection to ensure both histograms appear normally distributed and similar **[2]**.

2.21.1. SCREEN: 68158_screenshot_6.mp4 00:30-00:34.

2.21.2. SCREEN: 68158_screenshot_6.mp4 00:34-00:42.

2.22. Now, click the **Zero** button labeled as **Background** to set this height as the background level **[1]**. Choose a second rectangle on a flat section on top of the line under test **[2]**.

2.22.1. SCREEN: 68158_screenshot_6.mp4 00:42-00:45.

2.22.2. SCREEN: 68158_screenshot_6.mp4 00:45-00:54.

2.23. Again, examine and adjust the histograms so they appear normally distributed and as similar as possible **[1]**. Click **Line under test**, then click **Ok** to save this height value **[2]**.

2.23.1. SCREEN: 68158_screenshot_6.mp4 00:54-00:58.

2.23.2. SCREEN: 68158_screenshot_6.mp4 00:58-01:03.

2.24. Next, click the arrow icon again to rerun the program **[1]**. Draw a rectangle near the rim of a single hillock or void in the image labeled **IMG compare** using the left mouse button **[2]**.

2.24.1. SCREEN: 68158_screenshot_6.mp4 01:25-01:28.

2.24.2. SCREEN: 68158_screenshot_6.mp4 01:28-01:40.

2.25. Adjust the rectangle to closely match the rim of the structure using the zoomed image, such as the one labeled **Relax crop [1]**. Refine the selected region so that the rectangle precisely encompasses the hillock or void **[2]**. Finally, click the **Save** button next to **IMG compare** to save the integral volume based on the pixel sum **[3]**.

2.25.1. SCREEN: 68158_screenshot_6.mp4 01:40-01:49.

2.25.2. SCREEN: 68158_screenshot_6.mp4 01:49-02:02.

2.25.3. SCREEN: 68158_screenshot_6.mp4 02:02-02:06.

Results

3. Results

3.1. Hillocks formed after current stressing showed heights typically around 190 nanometers, with the smallest clearly detectable hillocks at 34 nanometers and lateral dimensions of approximately 1 micrometer **[1]**.

3.1.1. LAB MEDIA: Figure 3. *Video editor: Highlight the regions within the red boxes*.

3.2. Electromigrated volume increased with the length of the line under test, as shown by the exponential trend line in the plot **[1]**.

3.2.1. LAB MEDIA: Figure 4.

3.3. Electromigrated volume increased with higher current density, and two different thicknesses of encapsulating high-temperature silicon oxide showed different onset points for electromigration **[1]**.

3.3.1. LAB MEDIA: Figure 5.

3.4. At a lower current density of 2.56×10^{10} amperes per square meter, usable data demonstrated an increasing trend of electromigrated volume with increasing line length **[1]**.

3.4.1. LAB MEDIA: Figure 6. *Video editor: Highlight the dot points in the graph*.