Magnetic Domain Analysis of FMG Sample

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Magnetic materials have shown to be useful in the storage of computer data. Bell Labs developed a type of material known as ferrimagnetic garnets (FMG). This material allows for direct observation of magnetic domains. Using polarizing microscopy a pattern of "light" and "dark" areas will form. These areas are the magnetic domains of FMG. The lab will attempt to characterize the magnetic properties of FMG by analyzing the magnetic domains and quantifying the magnetization of the sample.

Ferrimagnetic garnets (FMG) was developed by Andrew Bobeck and Co. from Bell Labs. Bell Labs sought after a material that could improve memory technology using magnetic "bubbles". These "bubbles" emerge from the magnetic domains of the material. The material they developed FMG is a highly uniform film that could store to about five billion magnetic bubbles. Part of the development was to fill the gap between the costly high-speed memory and inexpensive slow speed memory technology that existed [1]. Although, FMG and bubble technology was quickly replaced by other emerging memory technologies; FMG can be studied and the formation of magnetic domains can be observed.

FMGs are grown on the face of a thin single crystal film. The direction of the magnetic domain formation is normal to the film and the magnetization vectors point into or out of the film. The material used is $Bi_{.6}Tm_{2.4}Ga_{1.15}Fe_{3.85}O_{12}$, is about 8 μm thick, and is transparent to visible light [2]. Using polarizing microscopy we will be able to observe the magnetic domains as adjacent areas of "light" and "dark". We will attempt to characterize the material by its magnetic properties by analyzing these magnetic domains, obtaining magnetization values, and plotting a hysteresis loop.

I. RELEVANT THEORY

I.1. Magnetic Domains

Magnetic domains are regions where the magnetization is in a uniform direction in a magnetic material. These regions can characterize the magnetic behavior of a material. In an un-magnetized state a material will have magnetization pointing in different directions within each magnetic domain. When an external magnetic field is applied to a material the domains will align with one another. The point in which applied external magnetic field can no longer increases the magnetization of the material is called saturation. All magnetic domains are fully magnetized in the same direction in a saturated material. The formation of these magnetic domains will therefore be dependent on the inputted magnetic field strength.

I.2. Faraday Effect

The Faraday Effect occurs during the interaction between light and a magnetic field. The effect will cause a rotation of the plane of polarization proportional to the magnetic field.

The Faraday effect will allow us to see magnetic domains in FMG film. A beam of light of linear polarization when incident on a magnetic domain will rotate along the plane of polarization due to the Faraday effect. In an un-magnetized state this will correspond to an equal amount "Light" and "Dark" area that would be observed in the sample. This is because an un-magnetized state will have an equal amount of magnetic domains with magnetization pointing into and out of the sample. The opposite pointing magnetization will cause the light to rotate differently for each magnetic domain causing the light and dark areas. The patterns will be readily observable and the amount of light and dark will give a the magnetization of the FMG sample.

I.3. Magnetization Loops

Ferromagnetic will exhibit a hysteresis loop of magnetization. This means the amount of magnetization will depend not only on the magnetic field passing through the sample but will also depend on the history of the field strength. In an un-magnetized state the area of light and dark will be equal to one another. As the magnetic field increase one of the domains will grow in area as the other shrinks. This process will help quantify the magnetization of the FMG sample. Assuming the net magnetization is proportional to the difference of the area of light and dark [2]:

$$m = \frac{M}{M_{sat}} = \frac{A_D - A_L}{A_D + A_L} \tag{1}$$

Where in (1) M_{sat} is the saturated magnetization and m is the normalized magnetization.

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As mentioned before the magnetization of the sample will be dependent on the history of the magnetic field strength. This would mean how the way the magnetic field strength was increased/decreased will affect the magnetization. We could then graph normalized magnetization vs normalized magnetic field strength (M-H). This graph will show a Hysteresis loop [2]. In this experiment we elected to not rigorously calculate the normalized magnetic field. This is because the field strength is directly proportional to the current traveling in the coil producing it. Since the current is directly measuring this would mean the graph of the normalized magnetization vs current will match the M-H loop. Thus we will see the hysteresis loop regardless. However, this loop can be characterized into two types.

I.3.1. Hard Magnetization

As the magnetic field is decreased, reversed, and taken back to saturation the magnetization will follow the applied magnetic field strength less closely resulting in a M-H loop that will bound a significant area. This area correspond to the work put in producing the magnetization or stored energy. This type of magnetic material will remain magnetized after the removal of external field such as in permanent magnets.

I.3.2. Soft Magnetization

After saturation the magnetization of the sample will remain constant with increasing magnetic field strength. As the magnetic field is decreased, reversed, and taken back to saturation the magnetization will follow closely to the applied magnetic field strength resulting in a narrower M-H loop. This will mean that when no magnetic field strength is applied the material will be unmagnetized. This would mean that we would expect the loop to cross through the origin. Less work needs to be done overall and the stored energy will be lower than that of Hard magnetized materials.

II. EXPERIMENTAL PROCEDURE

II.1. Materials and Devices

The experiment had a relatively simple setup. The FMG sample was mounted in the bore of a field coil (300 turns), placed between two cross polarizers. The magnetic field will be produced by the field coil which is powered by a direct current from a controllable power supply. A microscope connected to a digital camera was used to observe the pattern of the magnetic domains. The camera was connected to a computer which ran an image capturing software. The software allowed for a live feed of the sample as well as the ability to capture images at 2048×1536 resolution.

II.2. Procedure

The experiment was conducted on two separate days. The first day images for both hard and soft type were taken but due to incautious file labeling the images for soft type were ultimately unusable. The soft type was thus repeated and labeled correctly.

II.2.1. Hard Test

The sample was first un-magnetized. This was done through an 'eyeball' estimate. Positive and negative current was applied to the sample until the areas of the magnetic domains in the FMG seemed equal (ignoring artifacts) as shown in Fig. 1. The current was then increased incrementally in steps of 50mA all the way to 450mA. The current was then decreased to zero and then reversed to negative current. This was increased again to -450mA and then decreased once again back to zero. The current was again reversed (positive) and increased back to 450mA. These images can be seen in Fig 7. The images were all saved as `.png` files and later analyzed as described in the data analysis section. T

FIG. 1. These is an example un-magnetized state. Both Hard and Soft type was un-magnetized in this way.

II.2.2. Soft Test

The sample was again first un-magnetized again as in Fig 1. The current was then increased incrementally in steps of 10mA all the way until saturation. This was again another 'eyeball' estimate. The point where saturation was determined is shown in Fig. 2. The current was then decreased to zero and then reversed to negative current. This was increased again to saturation and then decreased once again back to zero. These images can be seen in Fig 8. The images were all saved as `.png` files and later analyzed as described in the data analysis section.

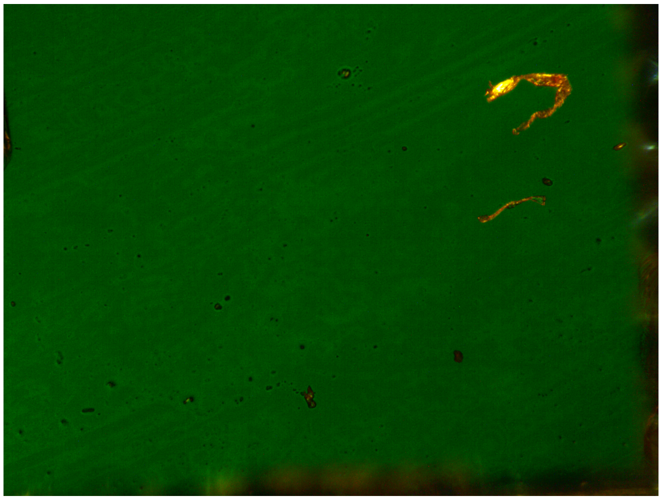

FIG. 2. These is an example complete saturation state. This example image shows an positive (applied current) saturated state. A negative saturated state would appear completely yellow.

III. DATA ANALYSIS

Using Python we were able to obtain magnetization information of the FMG sample. This was then used to create an M-H loop. The code, as shown in the Appendix, processes the images with visible 'Dark' and 'Light' magnetic domains to obtain a size (in pixels) of the area covered by each magnetic domain. This then allowed us to use (1) in order to obtain the normalized magnetization. The image process was repeated for each captured image in both the Hard and Soft tests. Packages `numpy`, `matplotlib`, and `skimage` were used.

III.1. Converting RGB Images to Magnetization

The main objective of the analysis is to convert the captured images into a magnetization values. The process involved first converting this image into a binary image as shown in Fig. 4. This would be useful as it will reduce the image will to '`1`' or '`True`' values. A simple sum of the values of the binary images will give us the total area covered by a magnetic domain. To do so we must also be able to distinguish the 'Light' and 'Dark' area; shown physically as the yellow and brown areas in Fig 1. The following describes the steps the our code took to obtain magnetization values.

III.1.1. RGB to Gray

RGB Images must first be converted to a gray-scale. This is to make it easier to later convert the images to binary values. RGB carries 3 values per pixel corresponding to Red, Green, and Blue whilst the gray-scaled image will only carry 1 value per pixel. Using an imported package called `skimage` [3] the image was converted to gray-scale. This package calculated each pixel as the weighted sum of the 3 values per pixel. The values were weighted as such to best represent human perception of red, green, and blue. This sum will give a single value per pixel and in whole would create our gray-scaled image.

III.1.2. Gray to Binary

The conversion from gray-scale to a binary image is simple and was defined directly in the code. Each element in the gray-scale image will correspond to a single scalar number ranging from $0-1$ corresponding from dark to light. This scalar number was then binned and changed to a 1 if it was higher than the low bin, it was changed to 0 otherwise. The low bin value were determined by first binning all values in the gray-scale image into 100 distinct bins. Fig 3 shows two peaks arising from the 100 bins, one for light and one for the dark domains. We had then binned the lighter peak (at .4) obtaining a binary image as shown in Fig. 4.

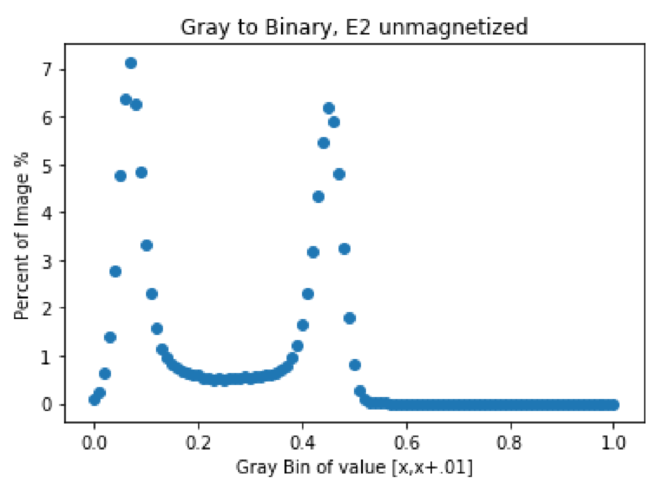

FIG. 3. This shows binned values as a percent of the images. The image shows the distribution of the binned values from an un-magnetized FMG sample.

III.1.3. Dealing with Artifacts

As shown in Fig. 1 and 2 there are artifacts that could change the calculated magnetization. We cropped our images into square images to remove these major artifacts

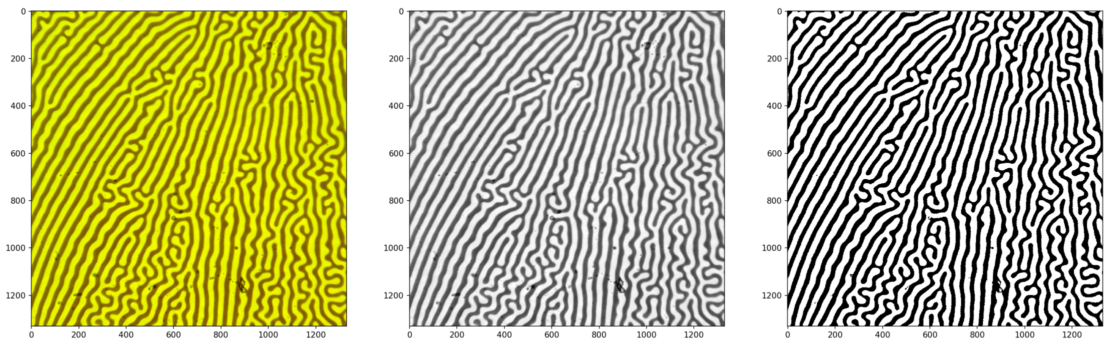

FIG. 4. This shows the image process from rgb to gray-scale to binary image. As described the images were cropped to remove any major artifacts.

reducing the error in the magnetization value. Cropping is a justified method of removing the artifacts as the magnetic domains are distributed randomly across the sample. This would mean the magnetization obtained across the whole sample will be the same as the magnetization across a cropped region of the sample.

Cropping however, did not remove smaller artifacts. These artifacts showed up mainly in the form of black dots. In determining the magnetization value these smaller artifacts will contribute the most to the error and is in part how the error in the magnetization was calculated.

III.1.4. Obtaining Magnetization

The binary image is outputted as an array of 1's and 0's with values of '1' being a 'light' area and '0' being a 'dark' area. Using numpy the sum of this array was obtained. This directly corresponds to the total light area A_L of the FMG sample. The total area of the dark sample A_D was obtained by subtracting total light area from the image size or total number of pixels. Using (1) we can then obtain the magnetization values for each image. The error was obtained by determine the number of pixels or area of the artifacts that were remaining (small black dots).

IV. RESULTS & DISCUSSION

The Appendix contains the code and a 'Jupyter Notebook' detailing the exact steps and process of the code. The main result is the hysteresis curves which are shown in Fig. 5 and Fig. 6

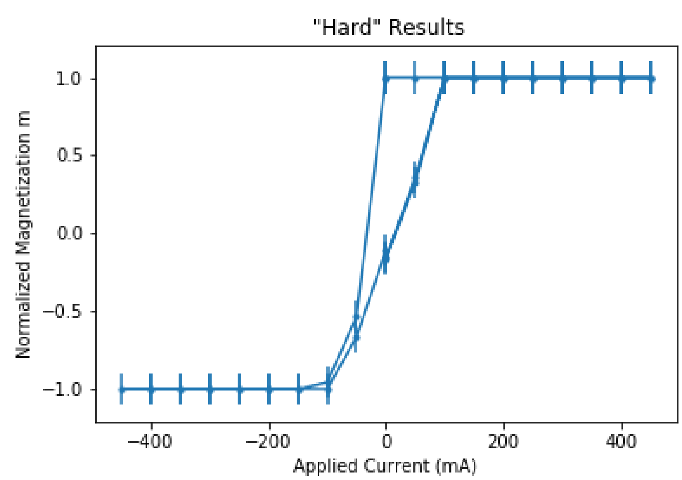

FIG. 5. This shows the results for the Hard type test. The path traced out by the measurements is shown and is a hysteresis.

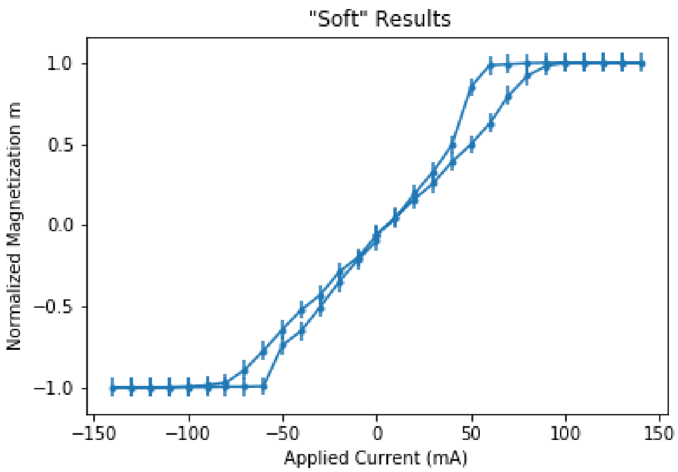

FIG. 6. This shows the results for the Soft type test. The path traced out by the measurements is shown and is a hysteresis.

IV.1. Hard Test

The results for the 'Hard' test for the FMG is inconclusive. Fig 5 shows that with increasing current the FMG sample does saturate and stays saturated. The FMG sample stays saturated even as the current is decreased as well as when negative current is applied. The sample eventually de-saturates from 'light' and quickly saturates to 'dark'. It is on the way up that the sample begins to behave unexpectedly. Rather than staying 'dark' saturated for decreasing negative current, the FMG de-saturates well before 0A is reached and completely de-saturates at 0A. As shown on the graph there is no distinction between the first time the current is increased from 0mA and the second time around the loop. Fig 5 also appears to be very jagged and sharp. This is due to the measurements being taken at 50mA steps. Fig 5 shows a one and a fourth of a loop. The extra fourth was taken after the full loop and for hard type materials we this increase after one loop to behave differently than the initial increase.

IV.2. Soft Test

The 'soft' test for the FMG shows that the material definitely exhibits 'soft' type magnetization. As shown in Fig. 6 the sample does exactly what was expected. It never stays fully saturated. It also does de-magnetizes when decreasing back to 0A as expected of soft type materials. The data points taken were in 20mA steps. This was able to generate much better curves for the hysteresis loop than the hard type.

IV.3. Magnetization Values

A clear table of the magnetization values at each applied current is in the appendix. There were two significant ways error could arise for normalized magnetization values. One of the ways would be that the remaining artifacts not cropped out have non-negligible area. This was quickly dismissed when we included in the program the amount of pixels these artifacts covered. We obtain a value of .0018 for the percent area covered by the small artifacts. That would mean the artifacts could only affect the magnetization by a value of at most $\pm$.0018. The second way was through seeing how off our magnetization value was in the un-magnetized state of the sample. It is clear when beginning each experiment there is no applied magnetic field and the sample should be in its un-magnetized state. As this un-magnetized state was 'eye-balled' at the beginning of each experiment this is a source of error. The clearest and simplest way to measure this error was to see how far from 0 normalized magnetization the inputted $0mA$ current was. This is where we get a value of .1 for the 'Hard Test' and a value of .05 for the 'Soft Test'.

V. CONCLUSIONS

Although the hysteresis is different than expected from a 'Hard' type material, there is still some comparisons that can be made. The hysteresis does act as a 'Hard' type for about half of the loop. On the other half the sample seems to have de-magnetized. This could be due to un-cautious measurements made overall in Day 1. This is a potential source of error that could be corrected with better measurements. More data points should have also been taken for the Hard test. Taking $50mA$ steps did not generally show the nice curvature of the hysteresis for Hard type material. It also made seeing the second increase in positive current difficult to see in Fig 5. For the 'Soft' type test, we clearly see the hysteresis loop traced out as expected. We can conclusively say the FMG sample can be have like a 'Soft' type material. It is clear from the results the soft test was done much more carefully and cautiously than the hard test. Overall the experiment was successful in demonstrating the nature of the magnetization in the FMG sample and we clearly observed soft type magnetization and hard type characteristics.

[1] ATT, Bell Labs *AT&T Archives: Bubble Generation* 1979

[2] Dept. of Physics, UML *Magnetic Domains* 2019

[3] Scikit-image *https://scikit-image.org/docs/dev/auto_examples/color_exposure/plot_rgb_to_gray.ht*

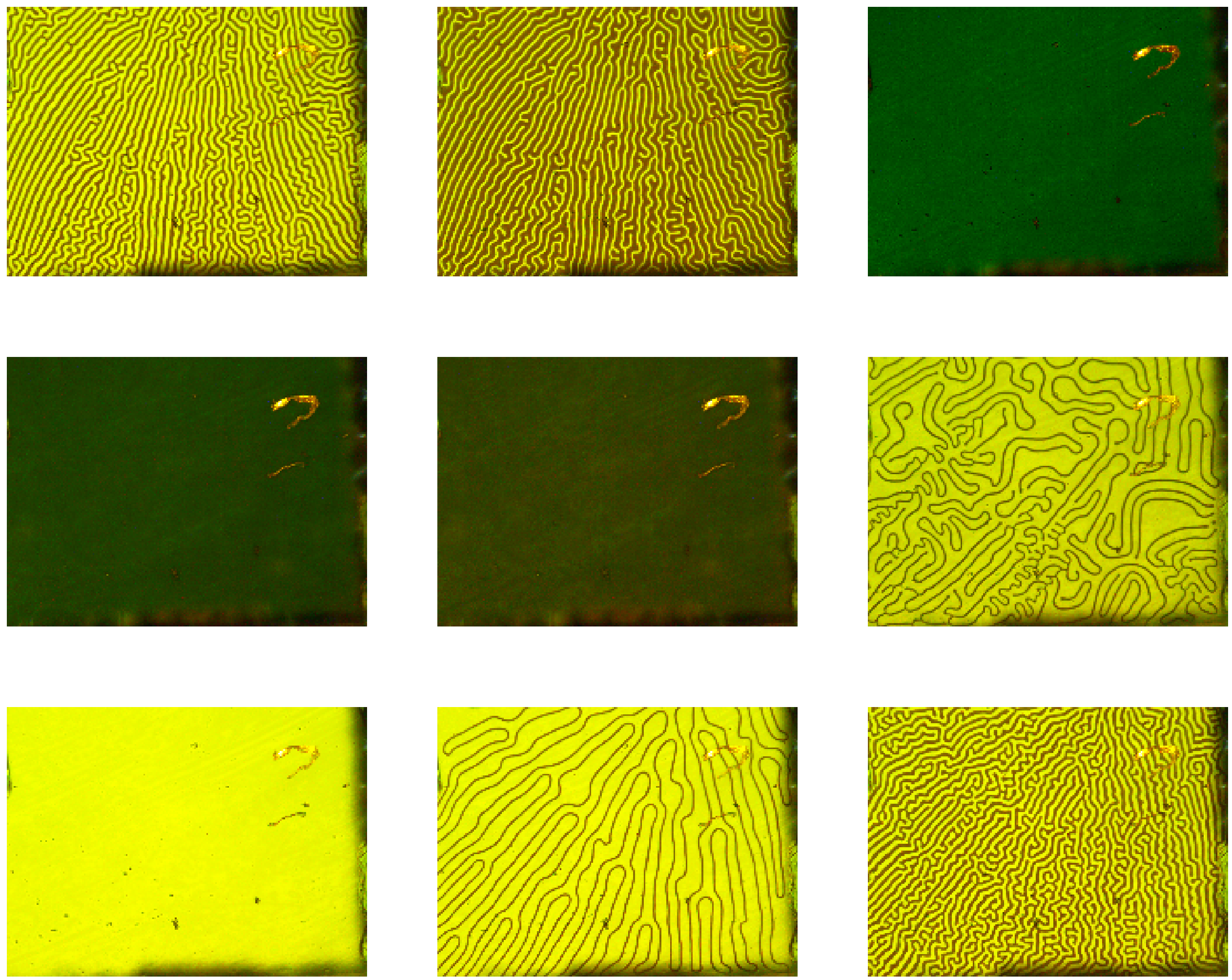

FIG. 7. Above shows different images from the hard test. They were captured at I = 0mA,50mA,450mA, 50mA,0mA,−50mA,−450mA,−50mA, 0mA respectively.

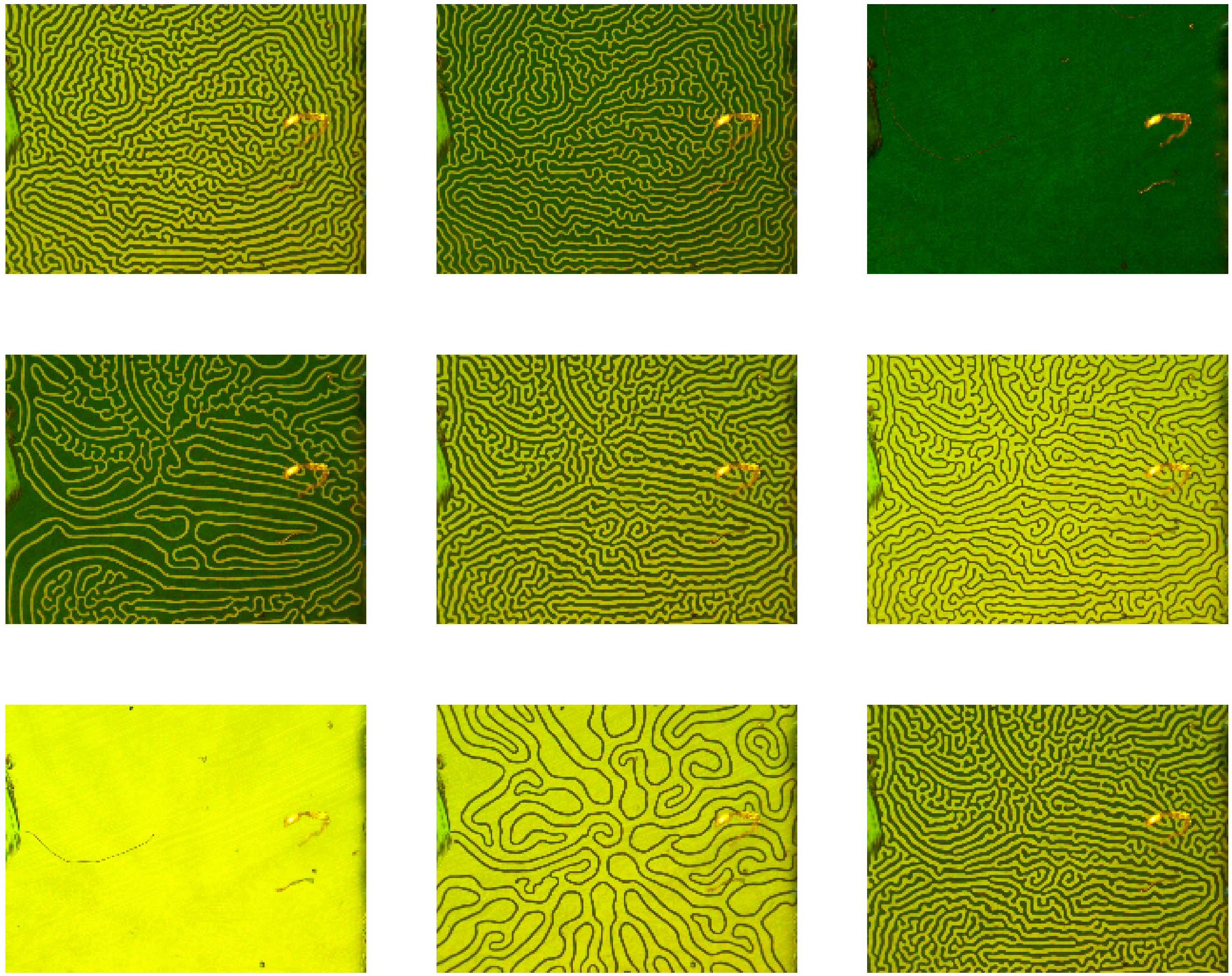

FIG. 8. Above shows different images from the soft test. They were captured at I = 0mA,40mA,140mA, 40mA, 0mA,−40mA,−140mA,40mA,0mA respectively.