FIB-Based Sketch & Peel for Fast and Precise Patterning of Large-Scale Nanostructures

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Introduction

FIB nanofabrication has proven to offer unique strengths, as demonstrated by numerous applications in R&D prototyping [1]. It helps to achieve scientific results faster by enabling *in-situ* optimization of patterning parameters and reducing the number of steps for the overall process. Moreover, the slow patterning speed of direct FIB milling itself (as compared to resist-accelerated lithography) can be overcome by the "sketch & peel" method. This approach has been proposed in the past for direct patterning of thin gold films [2]. Isolated metallic structures can be created by milling only the outline of the design elements and "peeling off" the unwanted gold areas with an adhesive tape method, instead of completely removing them with the ion beam. Here we further investigate sketch & peel as well as its applications employing various ion species. The combination of sketch & peel with high-resolution milling is shown for examples of plasmonic patterns. Furthermore, we have employed continuous writing strategies based on a laser interferometer-controlled stage movement to create a seamless groove across extended distances. This enables mm-sized patterns to be fabricated within minutes together with nm features at the same time, while still showing clean removal.

Sketch & peel method

Sketch & peel was first proposed by Y. Chen et al. for fast ion beam patterning of plasmonic structures on gold layers with Ga and He ions [2]. Instead of removing the layer material completely between the elements of a structure or array, the ion beam mills only the element outlines. The metal between these elements and outside the array can then be removed from the substrate by pasting and stripping a tape (figure 1).

Use of a low-adhesion layer is important for process reliability. Hence, no adhesive layer should be used between metal and substrate. Furthermore, the outline cut should be deeper than the metal layer thickness, to form a link between metal and substrate. Extensive investigations of possible resolution and pattern density can also be found in [2]. Obviously the throughput gain mainly depends on pattern density and element size, but can be orders of magnitude higher than usual FIB milling.

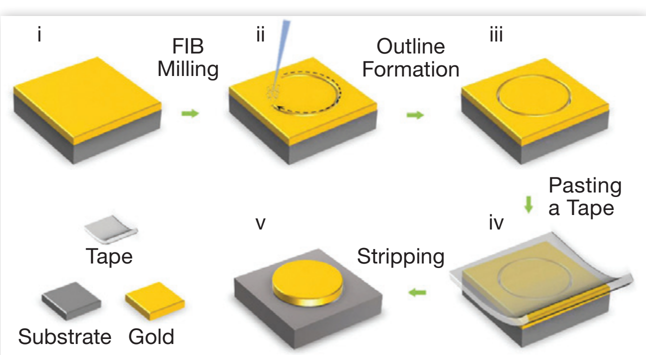


Figure 1: Principle of Sketch & Peel [2].

Ion Species

During this work we used a Raith VELION FIB-SEM Nanofabrication tool, which can be equipped with a Ga liquid metal ion source or with a liquid metal alloy ion source in combination with a mass separation filter to generate beams of different ion species [3]. Hence, we could perform experiments with Ga, Au, Si and Ge ions.

To evaluate the necessary line dose for a successful peeling step, we created circle arrays with varying doses for each ion species on samples with Si or SiO_2 substrates and 50 nm gold layers on top. An example of such a line dose test is shown in figure 2.

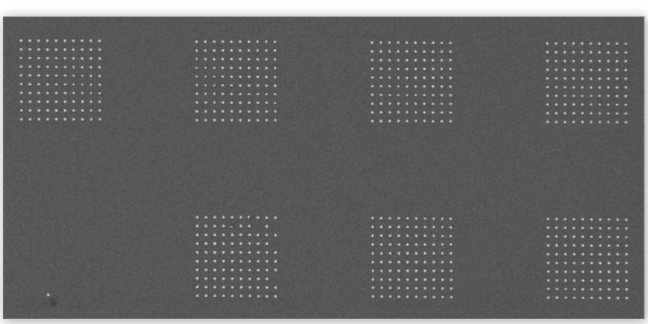


Figure 2: Test arrays of 800 nm circles after peeling, created with Au^{++} ions at different line doses (increasing dose from lower left to upper right array).

For low doses (low depth of outline cut), the circles are completely or partly removed during stripping the tape. Figure 3 shows close-up SEM views of circle arrays created with all our investigated ion species at doses where sketch & peel is reliably possible. The above-mentioned deeper groove into the substrate surrounding the gold islands can easily be seen in the SEM images.

The particular optimum line dose depends on the ion species and its milling rate, as well as on its beam diameter at a given beam current. Hence, lower dose is needed for one species if low currents with small beam size are used.

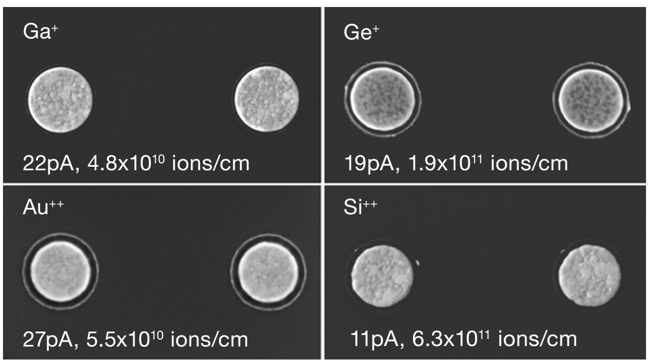


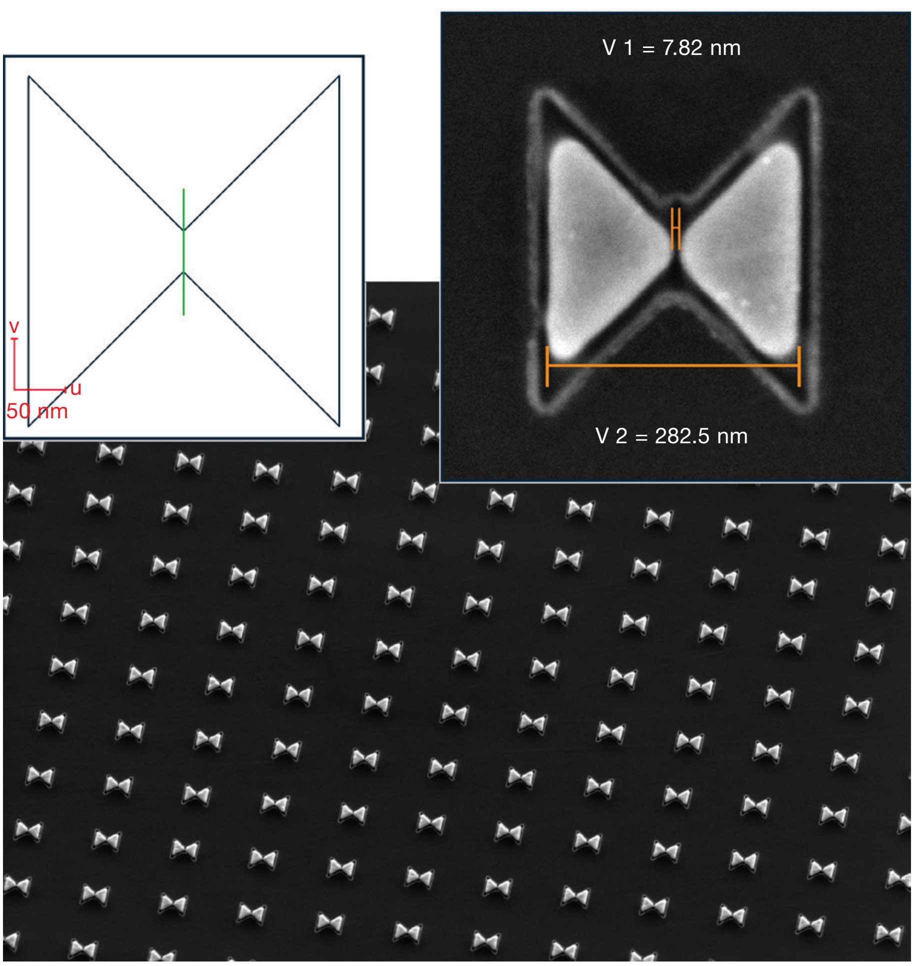
Figure 3: 800 nm circles created with 4 different ion species and corresponding optimum line doses for successful sketch & peel.

Obviously the adhesion of the fabricated metal elements is much higher than of the unprocessed layer, as the structures cannot easily be removed by performing an additional peeling step with a new tape.

Combination with conventional milling

Due to the high throughput of this process, large plasmonic arrays can be created with low beam currents and high resolution in a reasonable time. Furthermore, the elements inside these arrays can be combined with conventional low-dose and high-resolution cuts within the same milling step.

Figure 4 shows an example of such a combined process, with a 100 µm x 100 µm array of 10,000 bowties prepared on a silicon sample with 50 nm gold layer. Each single 300 nm bowtie is created by a surrounding deep outline cut and a final low-dose cut in the center to separate it into two triangles with sub-10 nm gaps. Here we used a beam current of only 1.7 pA Ga^+, resulting in 2 hours and 45 min process time. The gain in throughput is thus greater than a factor of 20 compared to conventional pure milling of the same array with the same beam current.



Another example of a plasmonic array is shown in figure 5. Here a 25 µm x 25 µm array of 625 gold nano-disks has been created by sketch & peel, including sinusoidal low-dose cuts inside the disks. This pattern could be milled within a mere 25 min at 1.7 pA Ga^+ beam current.

These kind of nanoparticle arrays were first created at Swinburne University using a mix-and-match process, where first an array of gold disks was manufactured using EBL and standard lift-off on a glass substrate [4,5]. The size of the disks was then reduced to the desired diameter and the cross cuts were added using ion beam milling. Compared to this more complex process, sketch & peel not only improves the overall process time, but also clearly simplifies the

Figure 4: Tilted SEM view of the inner part of a 100 µm x 100 µm bowtie array after peeling. The inlets show the bowtie design including low-dose cut in the center and a single 300 nm gold bowtie with sub-10 nm gap.

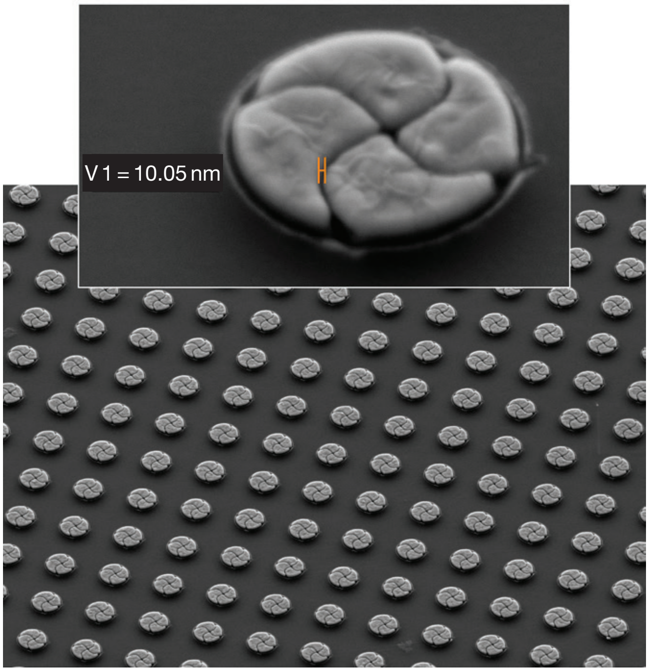


Figure 5: Tilted SEM view of a 25 µm x 25 µm gold nano-disk array with 1 µm period. The inlet shows a single disk with 500 nm diameter including a sinusoidal low-dose cross cut with 10 nm gap.

patterning process by reducing the number of process steps and avoiding charging effects from an insulating substrate, because the sample is completely covered by a conductive gold layer before the tape is pasted and stripped.

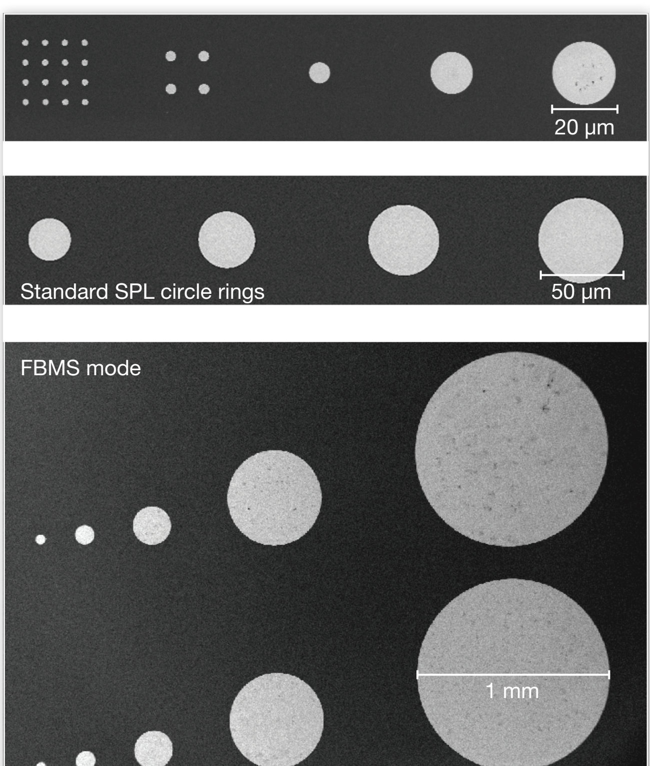


Figure 6: SEM images of gold circles with varying sizes. Circles over 50 µm were milled using FBMS (fixed-beam moving-stage) mode.

Sketch & peel for mm and cm size patterns

As the instrumentation used employs a real lithography architecture, including a laser interferometer stage enabling field stitching as well as continuous writing modes, we also investigated the suitability of sketch & peel for the fabrication of large elements and mm or even cm size patterns. Figure 6 shows test patterns with several circles of varying diameters. To mill circles bigger than 50 µm, we used the fixed-beam moving-stage (FBMS) mode of our instrument to create seamless grooves over large distances. Surprisingly, sketch & peel works reliably up to circle diameters of 1 mm, and milling one FBMS circle with 1 mm diameter takes less than 10 min at 30 pA Ge^{++} beam current.

The size can be even expanded if an array of milled dots is added to support adhesion inside the circle.

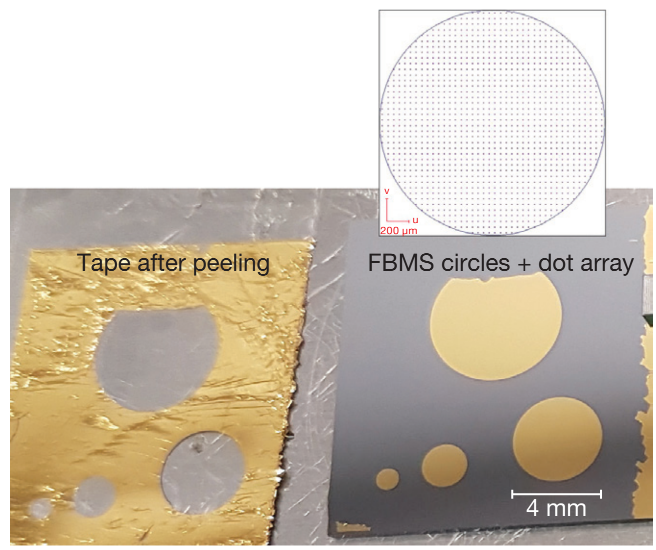


Figure 7: Photograph of gold circle sample, tape after stripping and FBMS circle design including dot array.

Figure 7 shows a test pattern with circle sizes varying from 1 mm to 6 mm and including dot arrays with pitches varying from 25 µm to 150 µm milled at 125 pA Au^{++}. The total number of dots was kept constant, at 1264 for each circle. Up to 4mm diameter and 100 µm dot array pitch, the circles still adhere to the substrate completely after peeling, whereas the 6 mm circle with 150 µm pitch only partly adheres to the sample.

By adding these adhesion-supporting dots to the design, some overhead might be taken into account as additional stage traveling and stage settling time contributes to the overall process time. However, creating structures which are easily visible is very unusual for a FIB milling process.

As a more practical example, we also used sketch & peel to fabricate large gold contact pad structures.

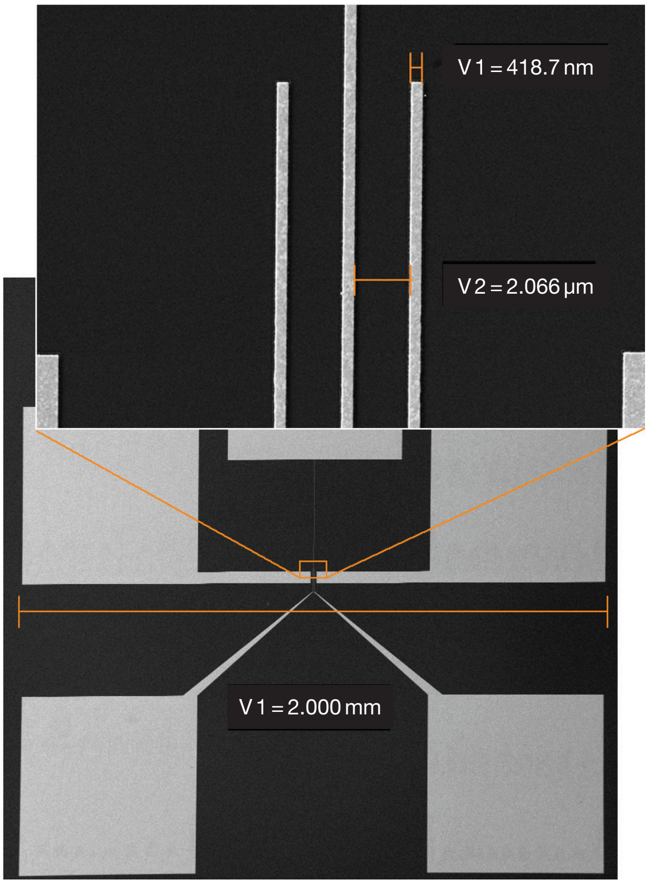


Figure 8: SEM images of a gold contact pad structure 2 mm in size, including 400 nm thick contact lines in the center.

Figure 8 shows such a structure, 2 mm in overall size, with 600 µm pads and 400 nm wide contact lines in the center which were milled within 3 min at 400 pA Ga^+ beam current.

A 4 x 4 array of these contact pad structures covering an area of 1 cm^2 is shown as a photograph in figure 9. Here 3 of the 16 contact pad structures are damaged as some parts of the pads or lines were unintentionally peeled off as well. However, this large pattern was fabricated in less than one hour, which is again extremely fast for a FIB based process. Removing the unwanted gold inside this array by conventional milling at the same beam current would result in a 3 orders of magnitude longer process time.

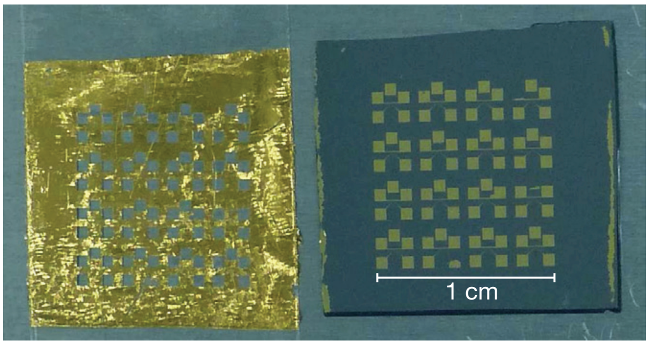


Figure 9: 1 cm^2 array of contact pad structures and the tape after peeling.

Conclusion

Sketch & peel is a reliable method of extremely fast FIB patterning for low-adhesion metal layers. Elements from <100 nm to >1 mm in size can be created, whereas combination with high-resolution conventional milling enables sub-10 nm features. Due to the high throughput, an accurate laser interferometer stage and fixed-beam moving-stage writing modes are highly effective at creating even cm size patterns. Other low-adhesion layers than gold might be investigated in the future.

References

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