Fabrication and characterization of home-built, low-temperature and ultra high vacuum compatible piezo stacks

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Piezoelectric actuators, also known as "piezos", are widely used in scanning probe microscopy applications to precisely move components by small distances in the nanometer range. Individual piezoelectric elements are often combined in stacks to multiply their motion. Unfortunately, commercially-available piezo stacks are expensive, especially if they need to be compatible with ultra-high vacuum and cryogenic temperature environments. Piezo stacks can cost up to 750 USD, though raw materials costs only 50 USD. This paper details a highly customizable fabrication procedure for low-temperature and ultra high vacuum-compatible piezo stacks. We detailed two methods of electrodes for fabricating the stacks and compared the pros and cons between the two fabrication methods. We used a home-built capacitance sensing unit to characterize the shear distance of the piezo stacks. Our home built piezo stacks with 3 mm by 3 mm surface area with two electrode plates shear about 1 um when the voltage of 400 V was applied, and the piezo stacks with 5 mm by 5 mm surface area with four electrode plates shear about 2 um with the applied 400 V.

I. INTRODUCTION

1 **[application of piezos in SPM]** A scanning probe microscope (SPM) typically employs stacks of shear piezoelectric plates to translate a tiny sensor across a macroscopic distance to approach a sample. FIND REFERENCES FOR BEETLE, PAN STYLE VARIOUS TECHNIQUE FOR SPM

2 **[Why do we want to build homemade piezo stacks]** Although prefabricated piezo stacks are commercially available, they are typically costly to customize, with customization being necessary for novel scanning probe microscopy designs. For example, for the purposes of a scanning four-probe microscopy setup, which employs over 60 stacks, commercial stacks cost nearly \$ 700 more per stack than material costs per stack for fabrication. However, the lack of pre-existing literature aimed at detailing precise methodologies for piezo stack fabrication can deter labs from in-house piezo stack fabrication. Here is some literature on piezo stack fabrication.[1–4] Needs additional review.

3 **[goals of paper]** In this paper, we describe a streamlined laboratory procedure to reliably fabricate and characterize piezo stacks from soft lead zirconate titanate (PZT) piezo ceramic plates. We designed a custom alignment fixture, which can be easily modified to fabricate stacks of varying sizes, to improve the efficiency and reproducibility of stack construction. To characterize the shear distance of the fabricated piezo stacks, we used a self designed, home built capacitance sensor to obtain the voltage-shear characteristics.

II. PIEZO STACK FABRICATION

4 **[Describe the piezo stacks and the components used]** The home-built piezo stacks detailed in this paper are of two kinds. The first kind is 3 mm $\times$ 3 mm surface area with two piezo plates sandwiched by two end plates. The second kind is 5 mm $\times$ 5 mm surface area with four piezo plates sandwiched by two end plates. Here we only detail the 5 mm $\times$ 5 mm piezo stacks process as the 3 mm $\times$ 3 mm style piezo stacks are of the same concept and are easier to fabricate due to fewer individual gluing process. The piezo plates PIC255 are from PI, ceramic end plates for 3 mm $\times$ 3 mm and 5 mm $\times$ 5 mm are PKJEP4 and PKFEP4 from Thorlab, respectively. 0.002" copper shim are used as electrodes which bond different piezo plates together. For gluing different surfaces together, EPO-TEK® H20E conductive epoxy, and EPO-TEK® H72 non conductive epoxy are used.

5 **[Describe why certain material is used]** PIC255 is a modified, soft lead zirconate titanate (PZT). This material exhibits very high Curie temperature, high permittivity, which is relatively easy to be polarized and hard to depolarize. The high Curie temperature ensures that during our bake out process of bonding different piezo plates together won't result to depolarization of the material. In addition, PIC255 has high coupling factor, high charge coefficient, which leads to relatively large displacement when relatively low electric field is applied. Finally the piezoelectric charge coefficient with respect to the temperature is very low for PIC255. Since the STM will be operated at very low temperature, thus maintain its structural and mechanical stability will result to the stability of the operation of the STM.

6 **[The process of making individual components/End plate with Copper shim, piezo plate sandwich, half stack, full stack, cure oven.]** This technical paper explores three distinct methods of fabrication. In the first method, two strips of copper shim are individually glued to each PIC255 plate using EPO-TEK® H20E epoxy, leaving at least a 1mm separation between the two shim. The individual plates are then cured for 2 hours at 120°C. Then, a half-stack is assembled. During the half-stack assembly process, an end plate is placed with electrodes facing up. Stripes of EPO-TEK®

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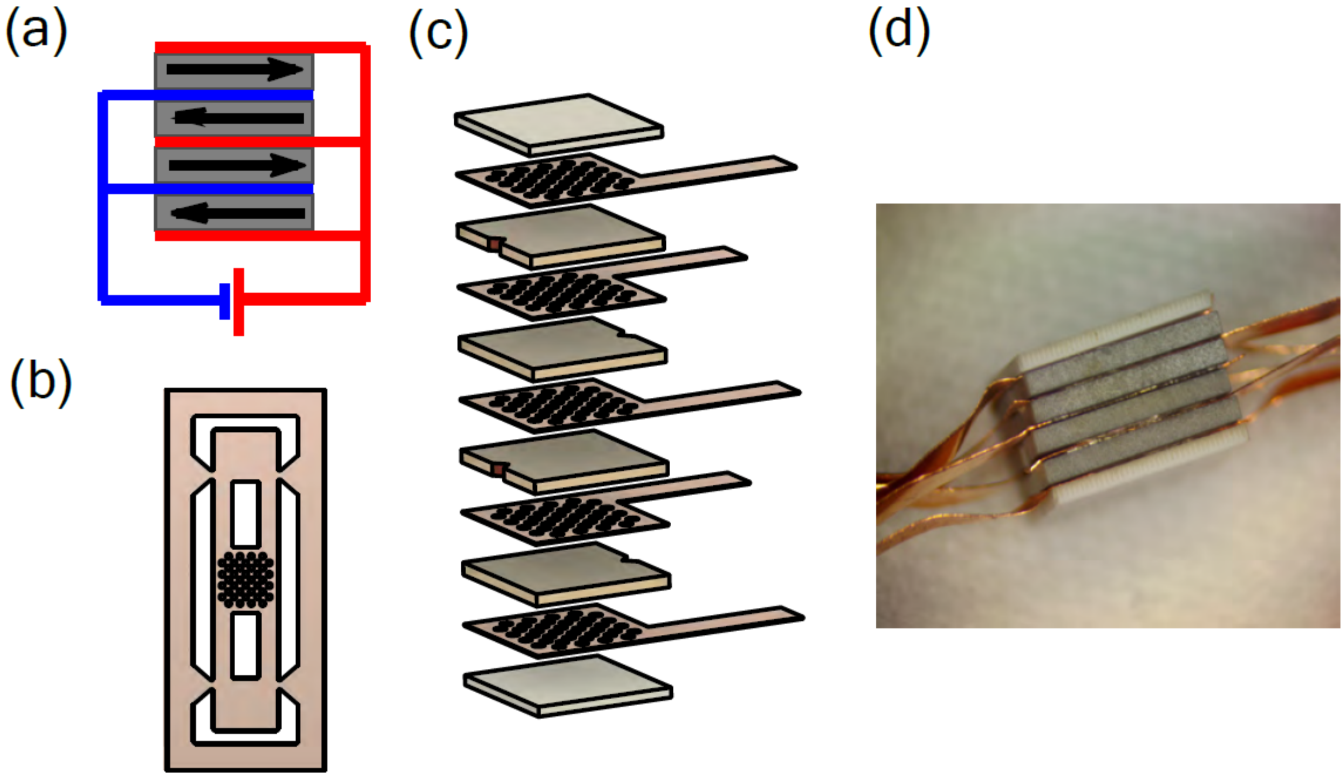

FIG. 1. (a) Exploded view of 5X5 Z-Stage Piezo Stacks. (b) Step-by-step fabrication process. (c) Custom stacking jig for alignment. (d) Final image of fabricated 5X5 Z-Stage Piezo Stack.

H20E epoxy are painted onto the surface of the copper shim and EPO-TEK® H72 epoxy is applied in the center of the plate for added reinforcement. To avoid epoxy spillage, leave a slight gap between the applied epoxy and the edge of the plate. Then, each subsequent PIC255 plate is aligned with the electrode facing up and the epoxies are applied in the same manner mentioned above, making sure to alternate the polarity of each plate. For set one of half stacks, a PIC255 plate without electrodes is glued onto the stack. For set two, do not paint epoxy on the uppermost plate and layer of copper shims. Using Kapton tape, a strip of copper shim is taped from the uppermost surface of the half stack to the steel alignment fixture. This process of electrically shorting the stack prevents any mechanical stress on the piezo plates from inducing charge differences that will be baked in during curing. The half stacks are cured for at least 2 hours at 120°C. During full stack assembly, epoxy is applied to the second set of half stacks, the first set is aligned on top (maintaining alternate polarities between subsequent PIC255 plates), the stack is electrically shorted, and the full stack is allowed to cure for at least 3 hours at 120°C.

7 **[method 2]** In the second method of fabrication. the copper shim was cut into an H-shape, allowing for easy alignment. Half stacks were assembled immediately, without prior gluing or curing of each individual component. Three stripes of EPO-TEK® H20E epoxy are painted on the surface of the H-shaped shear electrode. Small dollops of EPO-TEK® H72 are applied to both sides of the middle H20E stripe. The half stacks and full stacks are assembled in the same order as the copper mesh method and two-strip shim method and cured under the same conditions.

8 **[Method 3]** To bypass the long process of cutting the individual H-shaped shim in house with great precision, a copper shim of chemically etched pattern was professionally made (as shown in Fig.). The center was cut to cover the whole plate with a few small holes. Both sides of the electrodes were kept to later on decide which side to being cut based on the polarity of the need and the geometry of the assembly. The shape and surface tension of the copper shim allowed for immediate half-stack assembly. Due to the hole patterns in the center of the copper shim, the half stack is bound by H20E epoxy applied to the entire surface of the plate and copper shim (excluding the lead). The full stack assembly process is the same as for method two, however the omission of H72 epoxy means greater care has to be made when just using the H20E conductive epoxy. Since the H20E epoxy is less adhesive to H72 epoxy, thus enough H20E has to be applied, and the spillage of the epoxy has to be take care of afterwards to prevent the shortage of the stacks.

9 **[Alignment fixture]** A stainless steel alignment fixture, depicted in Figure 1c, was machined to allow easy alignment of piezo plates during the assembly process. A plate with tunnels cut out to the width of the PIC255 plates is screwed into the bottom body. An additional spacer was 3-D printed to

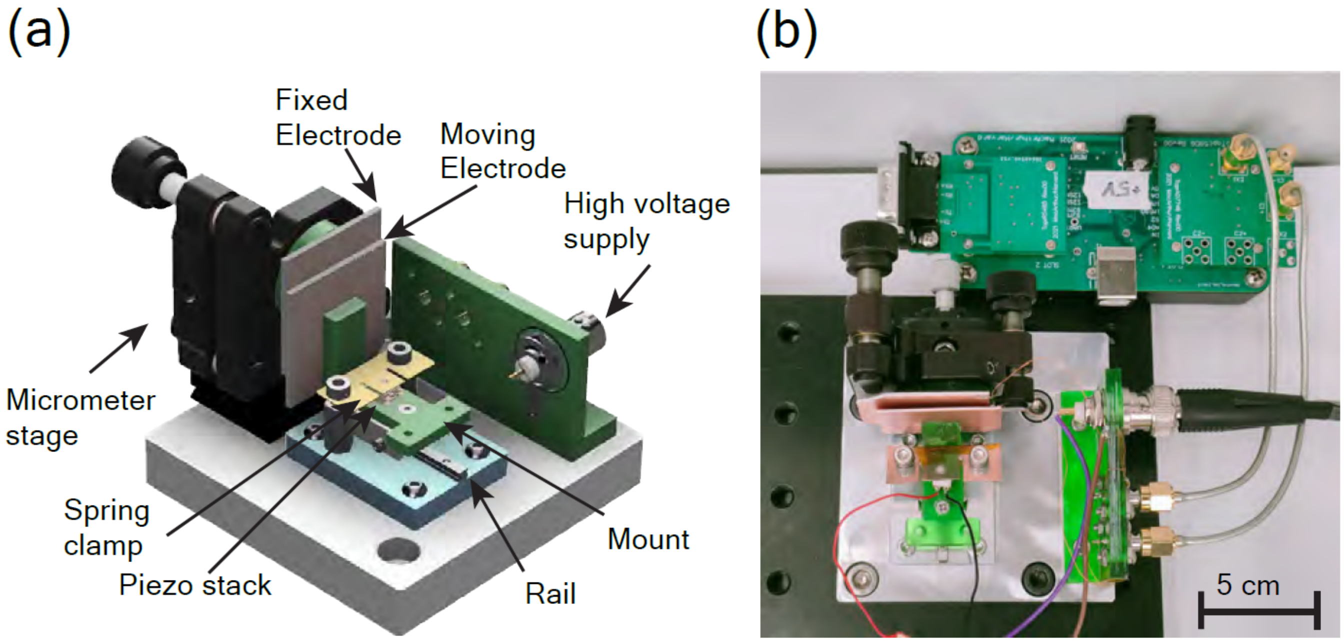

FIG. 2. (a) Capacitance sensing unit design. (b) Assembled setup.

fit in the tunnel. The plates are confined along three sides in this manner to prevent misalignment. This design emphasizes interchangeability; different plates can be machined for different dimensions of piezo plates, and with varying thickness for half-stack and full-stack assembly. The upper-most structure depicted in Figure 1c holds screws that can be fastened to apply pressure to the stacks during curing. The force applied by the fastened screw was non-uniform and often resulted in damage to the PIC255 plates. A more optimal method of compacting the stack during curing is to rest a weight on top of the fixture. To ensure contact between the weight and stacks, stack height can be temporarily increased by adding auxiliary end plates using Kapton tape.

10 **[Pros and Cons]** In-house fabrication of piezo stacks greatly reduces costs, particularly for systems requiring specialized dimensions or functions of the piezoelectric actuators. The benefit of reduced cost and increased customizability comes most obviously at the expense of time. Although method one produces robust and compact piezo stacks, the multi-step assembly process is tedious and time-consuming. The stack height of piezo stacks fabricated using method one, although lower on average, was subject to deviations due to the easy movement of the shim. Method 2 is the preferred method of piezo stack fabrication; the use of H72 epoxy enhances the robustness of the piezo stacks, the H-shaped shear electrode enables direct half-stack assembly and the relative thinness of copper shim to mesh produces more compact stacks. Method 3 produced stacks with uniform stack height and the easiest assembly process, but the omission of EPO-TEK® H72 epoxy made the produced stacks more susceptible to fall apart, hence enough H20E glue needs to be applied, and the over spilled glue has to be carefully scrapped off or sand off afterwards. Furthermore, commercially etched copper shim patterns might not be suitable for the application of just a few stacks due to the cost and large size of shim quantity.

III. CHARACTERIZATION

11 **[Why we need it]** To ensure the fabrication procedure produces high-quality, functioning piezo stacks, they must be individually characterized. We are interested in each stack's thickness and shear, since these two properties will determine how we can use the stacks for microscopy purposes. Thickness can be easily determined using a caliper to measure the height in the stacking direction. We aim for mostly uniform stacks, although small differences of less than half a millimeter are acceptable. Piezos of the same thickness should be used together, and groups with different thicknesses can be made equal by sanding the outer alumina plates as needed. Our fabrication procedure produced 4 plate piezo stacks with thicknes of 3.317 ± 0.2 mm. This distribution allows pairing stacks with very small differences in thickness that can be corrected.

The most important test is the shear characterization to ensure the quality of fabrication procedure. Piezos stacks are sheared by applying voltage in a saw-tooth or triangle wave with a given amplitude and voltage. Each time the voltage ramps up, the piezo gradually shears forward, moving their attached object by friction. If we use a triangle wave to drive the piezo stacks, the shear follows a hysteresis curve. Although we wish to determine the average shear of our home-made stacks, the actual values are not critical as long as they are in the range we desire (1-5 microns).

To characterize piezo stack shear, we devise a capacitance

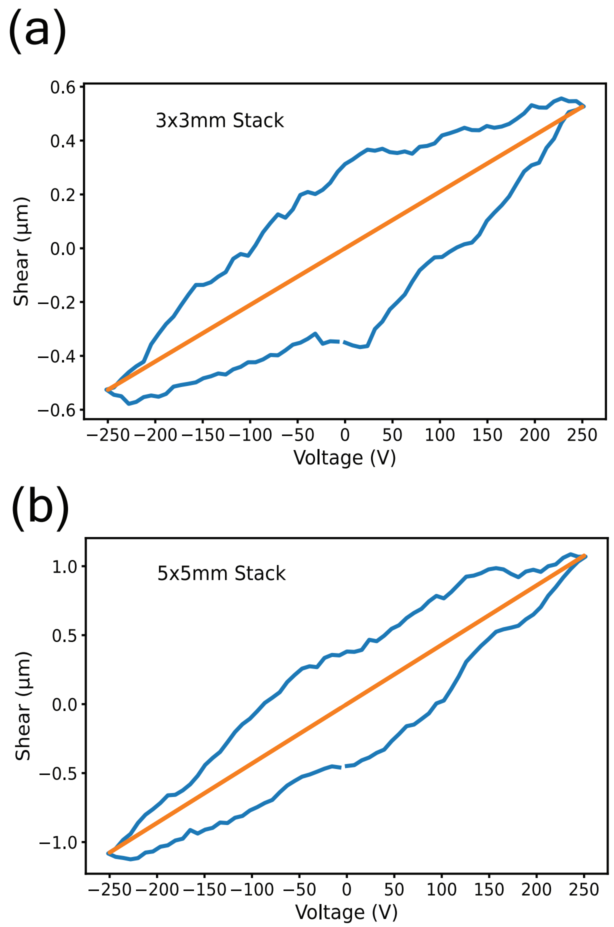

FIG. 3. (a) Shear plot for (a) 3x3mm and (b) 5x5mm piezo stack, including line used to calculate shear.

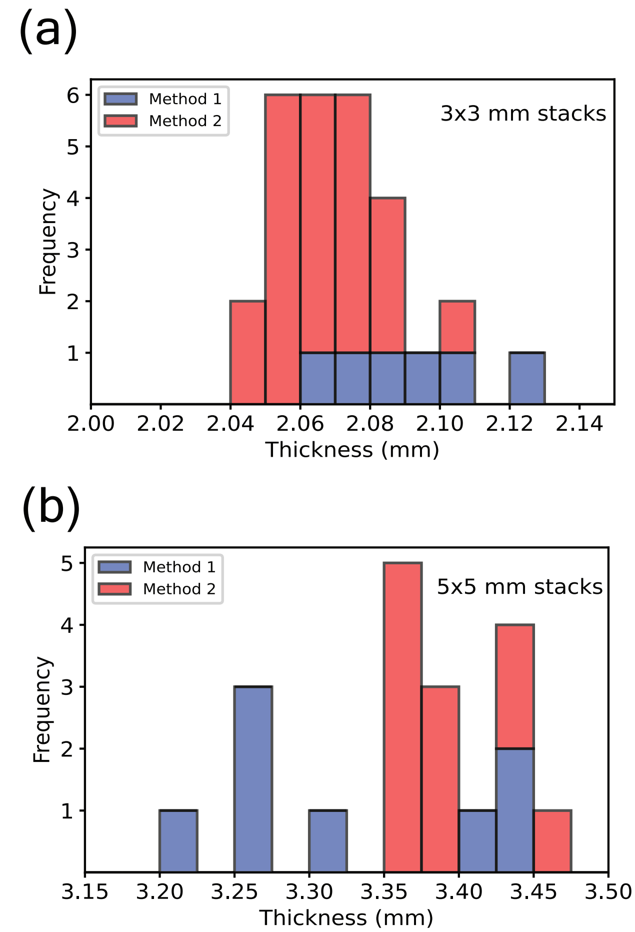

FIG. 4. (a) Shear plot for (a) 3x3mm and (b) 5x5mm piezo stacks, including line used to calculate shear.

sensing unit. There are other methods to measure small shearing movements, for example by interferometry, but those are quite expensive. Our goal is to device a simple apparatus that allows repeated measurement and minimizes costs. The basic principle of our method is using the piezos to change the distance between two electrode plates and measuring the resulting change in capacitance. The capacitance measurement relies on the non-linear relation between capacitance and the distance between two parallel plates, by the simple formula:

$$C = \frac{\varepsilon_o A}{d}$$

where C is the capacitance between the parallel plates, A is the overlapping area, d is the separation distance between the plates and ε_o is the permittivity of free space.

Our design has a ball bearing slider with a mount connected to a plate electrode. This is done to restrict the movement of the electrode, allowing only one degree of freedom. A piezo stack can then be clamped onto the mount, and when sheared, it moves the electrode. Another stationary electrode plate completes the capacitor to be measured. Restricting the movement of the moving plate with the slider fixes the overlapping area of the electrodes, which simplifies calibration. By measuring the change in capacitance, the shear can be easily characterized.

The characterization unit utilizes a 24-bit capacitance to digital capacitance sensor (Model AD7746) (Reference to manual) to measure the change in distance between two plates. This model measures capacitances in the picofarad range while being affordable. For better precision, mounting the stationary electrode on a micrometer stage is recommended to begin each measurement with roughly the same separation. The starting separation will depend on the sensitivity of the capacitance sensor used, but it is recommended to make the separation as small as possible to have bigger capacitance values. We found 1mm to be a good starting point. After a reasonable starting separation has been determined, the easiest way to calibrate is starting each measurement at the same initial capacitance.

For our measurements we drive the piezo stacks with a triangle wave to record their hysteresis curves. We use a Nanonis voltage supply (Model Reference). First, we validate our method by characterizing a commercial piezo stack, the Thorlabs PN5FC1. This model has a maximum shear of 7.0 microns when driven by a 200V amplitude triangle wave.[5] Our

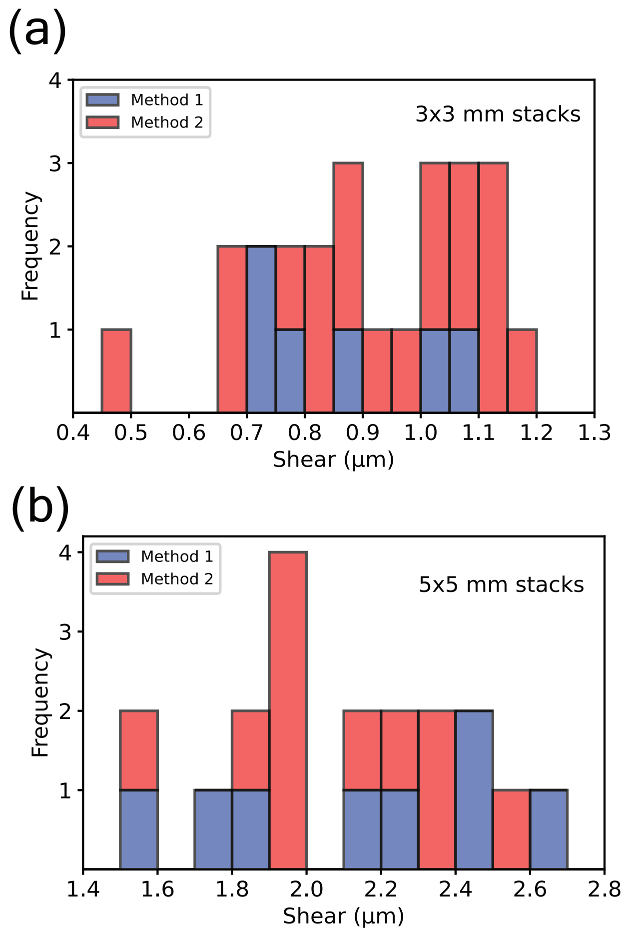

FIG. 5. (a) Shear distribution measured with our capacitance sensing unit for (a) 3x3mm stacks and (b) 5x5 piezo stacks.

characterization produces a hysteresis curve, with a shear of 6.52 microns (Figure 3a). The shear magnitude is determined by fitting the hysteresis curve to an ellipse. We repeat the measurements for our own homemade stacks. Figure 3b is the resulting curve for our stack #31, with shear 2.71 microns. Figure 4b displays the distribution curve of all the piezos we tested.

IV. CONCLUSIONS

12 **[Fabrication Successful, we consistently make piezos that work, with a consistent enough thickness. Saved money. We are using them in our STM.]**

The fabrication procedure developed by our lab consistently produces high-quality UHV-compatible piezo stacks that are currently being used for microscopy purposes. When characterized with our capacitance sensing unit, the home-made piezos behave similarly to commercially available stacks. The variation in their thickness is small and easily corrected by sanding. Although the process is time consuming, the versatility of our procedure allows for the customizability of piezo stack for many purposes, including different sizes, shears and directions. Most importantly, the raw materials needed to make the piezo stacks are 15 times more cost effective compared to commercially acquired stacks. Because of the time consuming process, we recommend using home-made piezo stacks for probe microscopy projects which need a considerable amount of actuators.

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