APPARATUS FOR STRAIN TUNING OF MATERIALS

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Abstract

This report outlines progress in the design and construction of an in-situ strain tuning apparatus suitable for spectroscopy and resistivity measurements. The apparatus utilizes a piezoelectric actuator to apply strain to the sample and a wheatstone bridge to measure the strain applied. The design takes into consideration the mechanical requirements of the strain apparatus, as well as the requirements that arise as a result of an infrared microscope's geometry. The apparatus is designed to conform to the dimensions of the existing infrared spectroscopy setup and will be used to investigate the effect of strain on the optical and electronic properties of materials.

Motivation

In Condensed Matter Physics, new experimental and instrumentation development allows for better understanding of material properties and how to tune them. For example, advancements in high-pressure physics has allowed for record temperatures of superconductivity in Sulfur Hydride[1]. Strain tuning is one of these techniques, and is a tried and true technique in changing the electronic properties of semiconductors[2],but sees less usage for probing the structure of correlated electron materials under spectroscopic analysis.

Existing work

The three methods of applying strain to materials are broadly epitaxial mismatch, anvil-based pressure cell, and piezoelectric based strain apparatuses. Epitaxial mismatch is done by controlling the lattice mismatch between the substrate, which is the platform that the film is grown on, and the film itself. This difference between the electronic structure of both of these materials creates strain in the film.[3] While this method produces very precise degrees of strain, it is impossible to change the amount of strain being applied after the material is grown, so observing phase changes that depend on strain is difficult, as changing the amount of strain requires the complete regrowth of a material sample. In-situ strain tuning apparatuses like anvil-based pressure cells and uniaxial apparatuses bypass this limitation, and allow for experimenters to mechanically tune the amount of strain being applied. Anvil-based pressure cells squeeze a material sample between two large anvils, which can apply large amounts of pressure to a sample. The disadvantage of this method is that it suffers from strong strain inhomogeneity which can cause failure. If the surface of the sample is too rough, there is a strong strain gradient created which can make it difficult to achieve repeatable strains[4]. Moreover, anvil-based pressure strains can only apply compressive, and not tensile strains. Finally, there are piezoelectric-based strain apparatuses which use piezoelectric materials to apply strain to a material sample. These materials generate a strain that is uniform and repeatable, This report outlines progress in constructing an in-situ strain tuning apparatus designed for usage with spectroscopic and resistivity measurements. In-situ strain tuning apparatuses are typically designed using piezoelectric actuators, which are electrically driven, and can be used to apply strain to a sample. They can be used to induce strain quickly and accurately, allowing for rapid measurements of phase changes due to changes in strain[4]. This type of strain tuning apparatus is particularly useful for spectroscopic and resistivity measurements, as it is easy to design it with access to the surface of the sample, a key consideration when doing optical and resistivity measurements. This report outlines progress in the design and construction of an in-situ strain tuning apparatus suitable for spectroscopic and resistivity measurements, based on a piezoelectric actuator.

Overview of Stress and Strain

Stress and strain are commonly used in the discussion of continuum mechanics, but their importance to this project merits some review. In an in-situ strain apparatus, typically speaking, involves compressing a spring, or pressurizing a gas reservoir, which pushes on an anvil that compresses the sample. In order for it to be a strain controlled apparatus, the spring constant (k) of the pressure source must be higher than the spring constant of the sample. Thus, the strain is the controlled parameter in the actual material. The material is modeled as a spring, where

$$k = Y\frac{A}{L} \qquad (1)$$

In this expression, Y is the Young's Modulus, A is the cross-sectional area of the sample, and L is the length of the sample.

This abstraction is very useful, as when we analyze the straining of a material sample, it is helpful to idealize the system as a set of coupled springs.The strain is a measure of the amount of deformation in a material. It is expressed as the fractional change in length of a sample,

$$\epsilon = \frac{\Delta L}{L} \qquad (2)$$

where ΔL is the change in length and L is the original length of the sample. It is a dimensionless quantity.

Stress is the force applied per unit area on a material. It is expressed as

$$\sigma = \frac{F}{A} \qquad (3)$$

where F is the applied force and A is the area on which the force is applied. Stress has the same units as pressure, which is usually expressed in Pascals (Pa).

Stress and strain are related by Hooke's law, which states that the strain is proportional to the stress. This is expressed as

$$\sigma = Y\epsilon \qquad (4)$$

where Y is the Young's modulus of the material and is a measure of its stiffness. When designing a strain-engineering project, it is important to consider the strain that the sample material will experience. This includes the magnitude and direction of the strain, as well as the effects that the strain will have on the material's properties.

The magnitude and direction of the strain can be determined by using strain gauges and strain indicators. Strain gauges measure the strain in a sample by measuring the change in electrical resistance due to the strain, while strain indicators measure the strain by measuring the displacement of a material due to the strain. Both of these methods are useful for determining the magnitude and direction of the strain. We are most interested in uniaxial strain, or strain limited to one direction.

Instrumentation challenges and solutions

In order to construct an experimental apparatus capable of straining these materials, we have several experimental concerns to take note of.

Firstly, the mechanical apparatus must be able to strain the material to a reasonable degree, both in terms of magnitude of strain and uniformity of strain across the entire sample. We must also take note of the environment in which the apparatus must operate, as the experimental conditions (temperature, humidity, etc) must remain constant and consistent.

Secondly, the apparatus must be able to tune the strain in an accurate and precise manner. This requires the apparatus to have a highly sensitive and repeatable strain tuning mechanism. Furthermore, the strain-tuning mechanism must also be able to accommodate the range of strain magnitudes required by the experiment.

Finally, the apparatus must be capable of being integrated with a spectroscopic setup. This requires the apparatus to be designed in such a way that it does not interfere with the spectroscopic measurements.

To address the first concern, we are in the process of constructing a prototype apparatus that utilizes a piezoelectric actuator to apply strain to the material. The piezoelectric actuator is placed on one side of the sample and either extends or contracts to apply a uniform compressive or tensile strain. We selected our piezoelectric actuators by looking at the Young's Modulus and elastic limit of various materials, and searching for piezo actuators that are capable of straining materials to their elastic limit. Our methodology for this calculation is to take a representative modulus of elasticity for a sample material, estimated to be around 100 GPa, in between the modulus of elasticity recorded for gold, 74 GPa (From Wang, L.: 'Investigation of the mechanical behavior of freestanding polycrystalline gold films deposited by evaporation and sputtering methods'. PhD thesis, Auburn University) and Titanium, 116 GPa (From the ASM materials handbook Vol 2, Properties and selection). The elastic limit used is 250 MPa, on the order of magnitude for metals. This is in between the elastic limit for gold, which ranges from 220-410 MPa (From Wang, L.: 'Investigation of the mechanical behavior of freestanding polycrystalline gold films deposited by evaporation and sputtering methods'. PhD thesis, Auburn University) and Titanium (140 MPa, From the ASM materials handbook Vol 2, Properties and selection). We assumed a sample with dimensions favorable for these measurements, which indicate a length of 5 mm and an area of 0.3 mm^2. Given all of this, we are now able to estimate the necessary force and displacement.

$$\frac{250\ MPa}{100\ GPa} \approx 10^{-3} \qquad (5)$$

This gives us the strain, which we then multiply by displacement to get

$$Displacement = 10^{-3} \times 5\ mm = 5\mu m$$
(6)

To find the required force,

$$F = 250MPa \times 0.3mm^2 = 75\ N \ (7)$$

This means that practically, we needed to find a piezo actuator capable of delivering at least 75 newtons of force

and 5 micrometers of displacement.
This is satisfied by the Thorlabs PAS005 piezoelectric actuator, and was what we chose to use in our design.

To address the second concern, we looked for the optimal way to measure strain, using a strain gauge. A strain gauge works by measuring the electrical resistance of a material when subjected to strain. The resistance of the material changes as its shape is changed, and this change in resistance can be measured. The amount of resistance change is proportional to the amount of strain that is applied. Since the change in resistances caused by the deformation of the strain gauge are relatively small, we are building a wheatstone bridge along with our strain apparatus itself, which will allow for us to precisely read small changes in resistance.

Finally, to address the third concern, we have designed the apparatus to conform with the dimensions of our existing spectroscopic set up, and ensured that the actuators and strain gauges are placed in such a way that they do not interfere with the spectroscopic measurements. This required us to take careful measurements of the vertical space available and make sure that the height of the apparatus ultimately be rather small.

Instrumentation Design

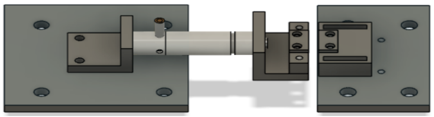

Figure 1: Table mounted strain apparatus

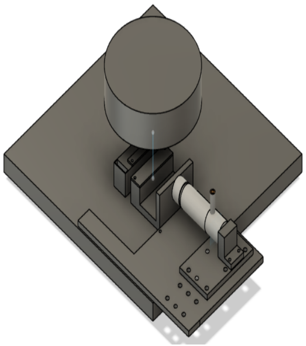

Figure 2: Microscope mounted strain apparatus

In Figures 1 and 2, I highlight two separate but similar designs for a strain apparatus. In the first design, the strain apparatus and actuator is mounted to an optical table. This allows for precise estimation of the amount of strain that a material sample can withstand. After this is done, the design in Figure 2 is mounted to the microscope and used to take measurements. The changes in the design of Figure 2 allow us to make changes to the tilt and positioning of the sample while we take our measurements.

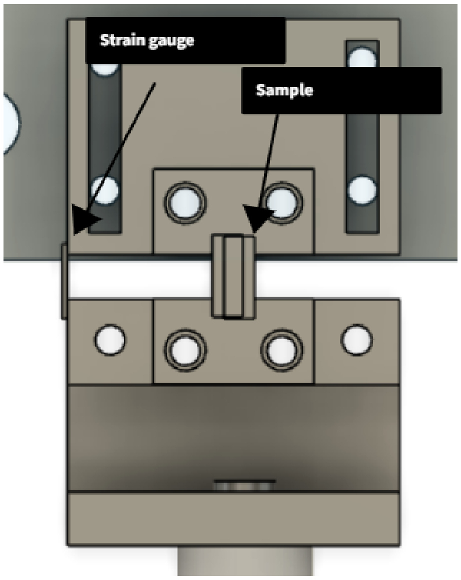

Figure 3: Mounting structure

In Figure 3, I show how the sample and strain gauge are attached. The sample is epoxied to two plates, one free to move with the actuator and the other fixed, and the movement of the actuator is what applies the strain and displacement to the sample. The strain gauge is epoxied to the side of the both plates, and the leads from it are connected to a wheatstone bridge circuit, which is used to measure the strain in the sample.

Future Directions

Overall, our design for the apparatus conforms to the identifiable requirements for a spectroscopic strain apparatus, and achieves the three goals outlined above. Currently, we are in the processing of assembling the parts for the design so we can take preliminary data. We have identified single crystal quartz and titanium dioxide as candidates for both testing of its mechanical, electronic and optical properties. Once we have finished assembling the apparatus, we will take our single crystal quartz and titanium dioxide samples and identify the maximal strain they can withstand, and then see how their optical properties change in response to strain.

Conclusion

The goal of this project is to create a strain apparatus suitable for spectroscopic and resistivity measurements. In order to do this, we took into consideration the mechanical requirements of the strain apparatus, as well as the requirements that arise as a result of our fourier transform infrared microscope's geometry. Taking these into consideration, we developed a design that utilizes a piezoelectric actuator to apply strain to a sample, and a wheatstone bridge to measure the strain. Furthermore, we designed the apparatus to conform to the dimensions of our existing spectroscopic setup. We are currently in the process of constructing the apparatus, and will be taking preliminary data soon.

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