Stress Measurements using the Picosecond Ultrasonic Method

Chris Korabik
Mechanical Engineering Department, Northwestern University
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This experiment employs the picosecond ultrasonic method of measurement to quantify the stress on a glass substrate with a thin film of gold deposited on it. Picosecond ultrasonics involves the use of high powered lasers to create and measure extremely brief and subtle acoustic waves within a material. By using a pump and probe laser setup on a thin film of gold over a glass substrate, we hoped to find that the period of oscillation for these acoustic waves changes upon application of an external stress. The oscillations found using this method are known as Brillouin oscillations [1]. The period of these Brillouin oscillations give us information about both the index of refraction and the speed of sound in the material [2]. From this information, the stress can be calculated at points throughout the entire thin film, giving us more information about both stresses in integrated circuits and about the practical applications of picosecond ultrasonics.

I. INTRODUCTION

The picosecond ultrasonic method can be used to make measurements on a very small scale to a high degree of accuracy. This method has specifically been used to calculate the thickness of a thin film of metal on a substrate without destroying the sample [3]. From this same method, the stress on the film and substrate can potentially be calculated. This information is important because the stresses exerted on these thin films have a significant impact on the performance of integrated circuits [3]. Excess amounts of stress on these thin films can lead them to buckle or delaminate from the substrate; knowing more information about how to measure the stress can help us better understand what causes computer chips to underperform [2].

The pump-probe method which was used for this experiment has been successfully used for measuring the thickness of a material accurate to less than an angstrom [3]. The goal of our project was to determine whether or not picosecond ultrasonics can be used to accurately determine the stress in a thin film on a substrate. For our project specifically, we analyzed a glass slide with a thin film of gold deposited on it. The laser probe which we used returns data which was used to find the period of Brillouin oscillations in the material. The value for the oscillation period could then be used to find the amount of stress on the substrate [2].

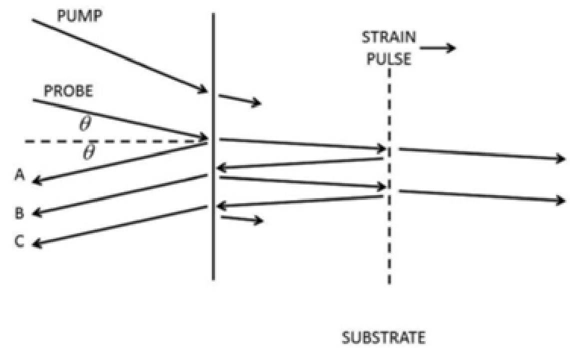

FIG. 1. Schematic diagram of the experiment taken from Dai et al. [2]. The pump pulse initially reaches the surface of the sample, exciting the electrons and causing the surface to heat up briefly. This creates a strain pulse which propagates through the substrate. The strain pulse locally changes the index of refraction of the material, so the probe laser is actually able to reflect off of the acoustic strain pulse.

II. EXPERIMENTAL METHOD AND APPARATUS

For this experiment, a pump and probe method was used to make measurements on a picosecond time scale. The pump laser is emitted in brief pulses which excite the electrons in the material, causing the temperature to rise [3]. This expands and contracts the material, creating sound pulses within the material. The second laser, the probe, emits pulses at the same frequency and measures the change in intensity caused by the sound waves in the material. The data received from the probe can be used to calculate a number of values, including the variation of stress within the material.

In a similar fashion to what is shown in figure 2, the pump pulse will first create strain waves within the sample. Since we cannot directly measure data on a picosecond timescale, the probe pulse is offset from the pump by moving a delay line mirror back slightly for each data point taken. The probe laser is reflected both off of the surface of the material and off the strain pulse within the sample, and the detector receives the superposition of each probe reflection (rays A, B and C in figure 1). Because of the delay change for each data point, the intensity received by the detector varies as a function of time. Therefore, from plotting each data point taken as the change in reflectivity versus time, we get results such as those shown in figures 4 and 5.

Northwesterns NUFAB facility was used for the deposition of both gold and aluminum films using E-beam evaporation. The pump-probe apparatus was used to create and measure the sound waves within the mate-

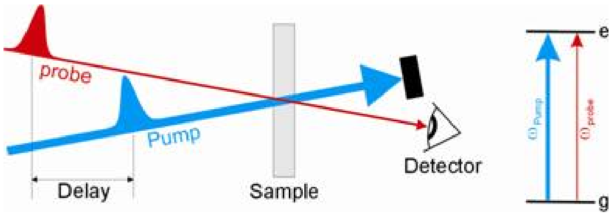

FIG. 2. Schematic diagram of the pump-probe setup as used by Robotham and McKimmie [4]. For our experiment, however, the detector will be on the same side of the sample as the incident laser pulse since we are measuring the change in reflectivity of the material. The detector receives reflected light both off the surface of the substrate and off the strain pulse within; depending on how far into the substrate the strain pulse is at a given time, the light at the detector will interfere either constructively or destructively.

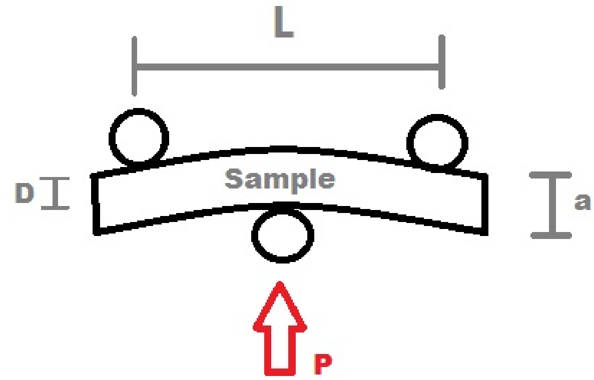

FIG. 3. Basic three point bend setup. The design for the stress application had to fit the available spacing while providing an accurate and controllable means of applying the stress to the sample. This apparatus allows us to calculate roughly what we expect the stress to be at the point of measurement; we hopefully can then know what to expect from the picosecond ultrasonic calculation for the stress.

rial, and the collected data was analyzed with the use of MATLAB programming. The stresses in the material were applied by bending the substrate.

For the application of a controlled strain on the substrate, a three point bending apparatus was designed to fit the constraints of the setup. A simple design for the stress application is shown in figure 3. The strain ϵ can be found using the following equation

$$\epsilon = \frac{6Da}{L^2} \tag{1}$$

where L is the length between the constraint points, a is the thickness of the sample, and the deflection D is the vertical displacement from where the sample was under no applied force [5]. From the strain value, the stress σ can be calculated by

$$\sigma = E\epsilon \tag{2}$$

where E is the Young's modulus [5]. The point of maximum stress and strain will be where the force P is applied to the wafer. After calculating the stress on the glass using this method, we hope to get similar, far more accurate results by using the picosecond ultrasonic method.

III. DATA ANALYSIS AND RESULTS

A MATLAB script was set up and served as the basis for computing the calculations in the experiment. Initially it was difficult to actually distinguish the Brillouin oscillations in our data from the noise; however, we were able to find several ways to improve our data so we could make more accurate calculations. Since the noise in the signal is random, we found that by taking multiple data sets from the same sample and taking an average, much of the noise would cancel. Doing this allowed us to clearly notice oscillations in the data; our results of five data sets are shown in figure 4, and their average is shown in figure 5, where oscillations are clearly visible.

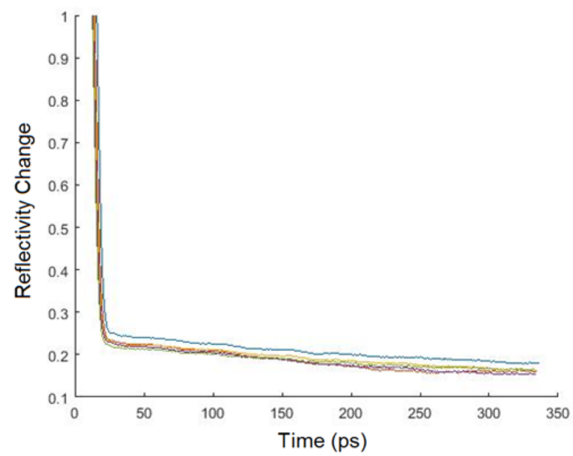

FIG. 4. Plot of the reflectivity versus time of 5 trials of the same point on a sample. This is a result from our setup using a 390 nm pump laser and a 780 nm probe laser on a glass substrate with a 10 nm thin film of gold.

The data from figure 6 initially looked similar to the plot in figure 5. We used a computer program to make a weighted average which gave us a curve of approximately only the background, and then we subtracted the weighted average data from the raw data. This yielded the data forming the green plot in figure 6.

Next, a Fourier transform was taken to give us the value for the period τ of the Brillouin oscillations.

In order to quantify the value of the frequency and period from the Fourier transform in figure 7, we fit a Gaussian function to the peak. The peak of the Gaussian function should ideally correspond to the true peak in the

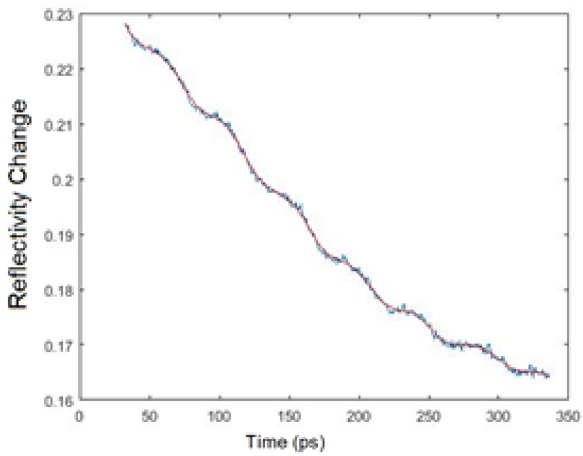

FIG. 5. Plot of the reflectivity versus time averaged over five trials on the 10 nm gold sample. The sharp peak shown in figure 4 was removed to improve the accuracy of subsequent calculations. Note that oscillations in the signal are clearly visible.

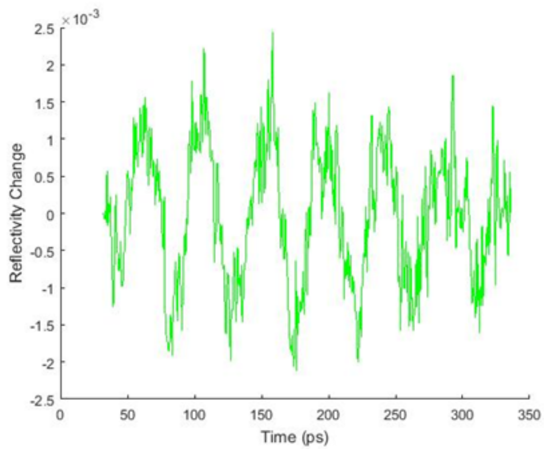

FIG. 6. Plot of the reflectivity versus time after the removal of the background for the data shown in figure 5. A weighted average was used to approximate the background, and that was subtracted from the data, leaving only the Brillouin oscillations and noise. Because multiple trials were averaged to remove the noise, this plot can very clearly show Brillouin oscillations.

frequency value of the Fourier transform from figure 7. The uncertainty values here were found to be the half width at half max (HWHM) of the Gaussian peak. The result is shown in figure 8. With more optimization in the code and the data, a shift in the frequency and period of the oscillations upon external stress application can become more apparent.

The period of the oscillations in reflectivity as a function of the time delay of the probe is

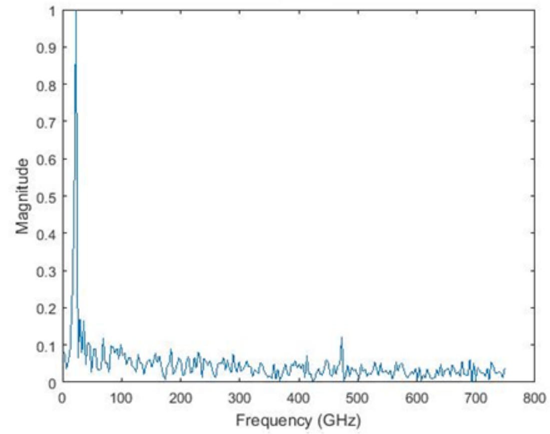

FIG. 7. Fourier transform of the data from figure 6. This shows the period of these Brillouin oscillations to be around 45 ps.

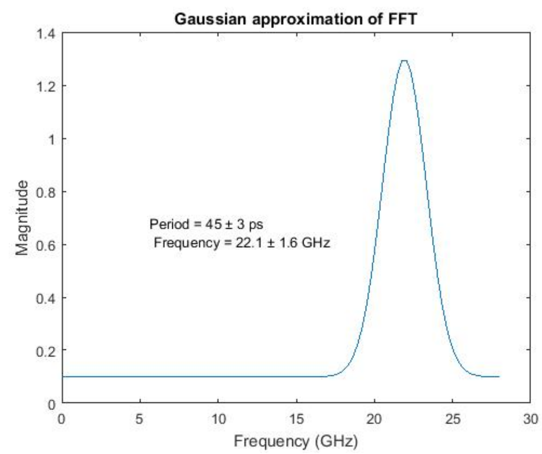

FIG. 8. Gaussian approximation of the Fourier transform in figure 7. The Gaussian function allows us to find the uncertainty in our measurement; this shows the period of these Brillouin oscillations to be $45 \pm 3ps$.

$$\tau = \frac{\lambda_0}{2nv * cos(\theta')} \tag{3}$$

where λ_0 is the wavelength of the light in free space, n is the index of refraction of the material, v is the sound velocity in the material, and θ' is the propagation direction of the probe beam once it has entered the substrate [2]. For our experiment, we positioned the light in a direction normal to the surface of the film, so the $cos(\theta')$ term could be simplified to 1. The value for the stress on the film is dependent on both n and v, so through calculating τ we can find the stress at a specific point on the film.

Initial trials were performed on samples of silicon, aluminum on silicon, and glass on silicon. The results for these samples did not provide reliable evidence of oscillations within the material. However, the Brillouin oscillations in the data were easily located when we used a glass substrate with a thin film of gold on it, as shown in figures 4-8.

After some time determining which setup approach would be best to find Brillouin oscillations, we determined that a 780 nm probe pulse and a 390 nm pump pulse would be the optimal choices. This is mainly because the detector we used was more sensitive to 780 nm light and because gold has a high absorption at 390 nm and high reflectivity at 780 nm. The 780 nm probe pulse was used so we could distinguish the difference between the pump and probe lasers.

IV. DISCUSSION

In order to clearly detect Brillouin oscillations, we found that it is absolutely essential to use a pump laser with as high of an intensity as possible. This ensures that the acoustic wave is created and propagated through the substrate. We also found that taking multiple data sets at the same point and averaging the data could help to limit the amount of random noise in the data. Using material that has a high absorption at the pump wavelength and a high reflectivity at the probe wavelength can also significantly improve the quality of our results. Using these methods of improving data collection can significantly lower the uncertainty in our measurement for the frequency and period of these Brillouin oscillations.

In the near future we plan to use our designed apparatus to apply a controlled strain onto our sample. By taking data on our sample with and without the applied stress, we hope to find a shift in the period of the Brillouin oscillations once the stress is applied. The period depends on both the index of refraction and the speed of sound in the medium, which are used to calculate the stress at the point of measurement.

The groundwork has been laid for the continuation of this experiment. From the potential change in oscillation period, we hope to be able to accurately calculate the change in the stress exerted on the sample. If this experiment is successful, we will have found a way to measure the stress in a non destructive way to a high degree of accuracy. This tool of measurement can then be used on computer chips to help find and limit any applied external stress. Ultimately we hope that picosecond ultrasonics will effectively be used to enhance the performance of electronic devices.

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