Strain in a Block of Silicon Due to Implantation and Relaxation of SSOI

by

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Abstract: The effects of strain**,** due to implantation of Al into Si and relaxation of SSOI, were studied. The question to answer, in studying the effect of strain as a result of implantation of Al into a block of Si, was “Is it possible to observe a change in the diffraction pattern of the Si block due to implantation". To answer this question the block was simulated in COMSOL by using thermal expansion as a replacement for implantation, and it was concluded that practically it is not possible. In studying the effects of relaxation of SSOI, a block of SSOI was simulated in COMSOL and the displacement fields as a result of the strain were studied at different heights of the insulator beneath the Si. For this part, some functions could be used to explain some behaviours of the displacement fields on top of the SOI.

Acknowledgment

I want to thank Prof. Ian Robinson for providing this project for me and for his support. In addition, I want to thank him for arranging a trip to Diamond light source for me, which helped me to become more familiar with the experimental side of a project like this project. Moreover, I want to thank Dr. Dorothy Duffy for accepting to become my second supervisor. Furthermore, I want to thank Ms. Xiaowen Shi for her help in the first section of this project and I want to thank her for her guidance and help in accessing the laboratory in B-1 of LCN building. In addition, I want to thank Dr. Gang Xiong for his help and guidance for the second part of the project and I want to thank him for booking the COMSOL computer in LCN building for me many times.

Introduction

Nanotechnology is becoming widely important, in fact, nowadays this technology is being used in many scientific field, such as, physics, chemistry, engineering and biology. There are two main reasons for importance of nanotechnology. Firstly, the increase in the influence of the surface molecules of an object to the overall properties of it can result in some very interesting features. For example, a piece of gold can be observed in other colours rather than yellow, if it is reduced in size dramatically to nano-scale. This is mainly as a result of the fact that the molecules on the surface have different bindings to other molecules compared to the molecules inside the object. In addition to different properties, nanotechnology is being used to achieve smaller size in many fields. For example, the 32nm process technology is predicted to become 11nm in 2015 [(1)].

In this project the effects of strain on two blocks of silicon were simulated and studied. Firstly, implantation of aluminium into silicon for production of p-type semiconductor was studied. In the second part of this project relaxation of Strained Silicon On Insulator (SSOI) was studied.

This project is divided into 3 sections. First section is about the effects of strain in a block of silicon due to implantation. Second section is about a one day trip to Diamond light source for becoming more familiar with the experimental side of a project like this project. Third section is about the effects of relaxation of SSOI.

Strain in a Block of Silicon Due to Implantation

Introduction and Background

Production of n-type and p-type semiconductors by implantation of ion into a semiconductor is a very important part of transistor and diode's manufacturing. That is why a very important question these days is "How small can transistors or diodes become by doping". The current transistors are 32 nm, which is "the expected average half-pitch of a memory cell" [(1)], and this number is estimated to become about 11 nm in 2015, as mentioned before. This current technology is achieved by using doped silicon, which refers to production of n-type and p-type Si. N-type Si can be produced by substitution of phosphorus into Si, which is replacing the Si atoms with P atoms to produce an excess of free electrons; this is due to the fact that P has one proton more than Si (see Figure 1). P-type Si is the opposite to n-type Si, and it can be produced by substitution of aluminium into Si.

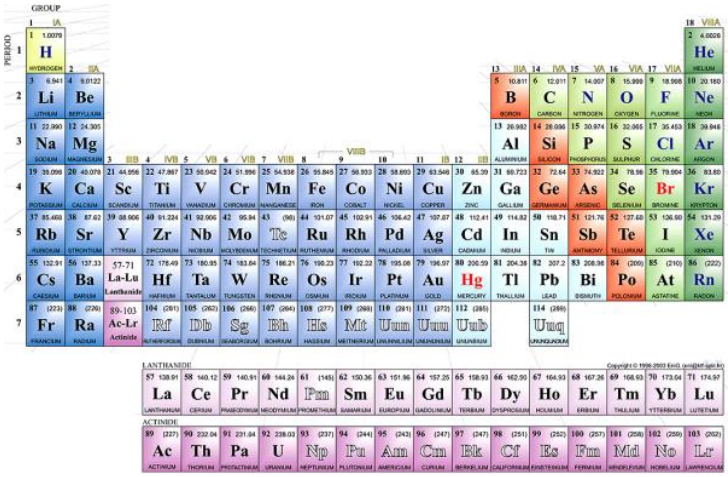

Figure 1: The periodic table of elements [(2)].

Joining n-type to p-type semiconductor can result in production of a diode that transfers the current in one direction only.

In this section the implantation of aluminium into silicon is simulated by using COMSOL program. The question that is going to be studied in this section is that, "Is it possible to observe a change in diffraction pattern of a silicon block, as a result of strain due to implantation of aluminium into the block of Si".

Methods

To achieve the answer to the question, represented above, a block of Si was planned to be simulated in COMSOL program. However, implantation could not be simulated directly by COMSOL; therefore, a thermal expansion in the implantation region of the Si block, see Figure 2, was decided to be used as a replacement for implantation.

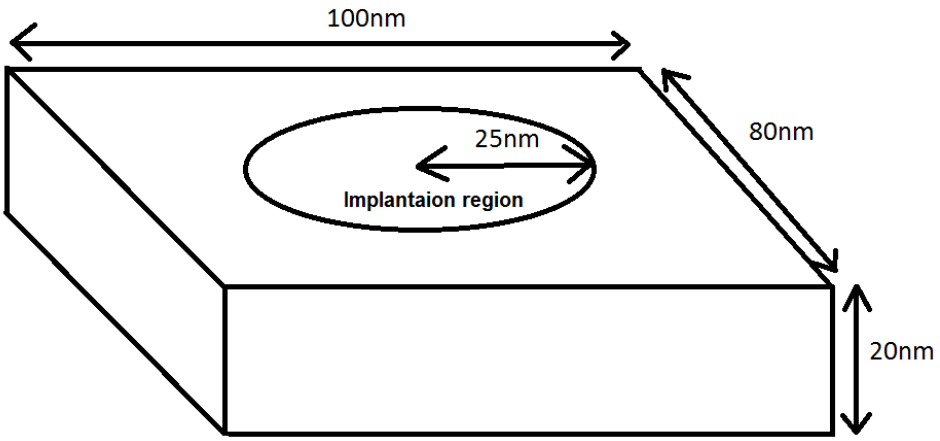

Figure 2: The implantation region inside the block of Si.

This plan requires relating the change in volume of the Si block due to implantation to a change in volume due to thermal expansion, which means relating the number of implanted Al atoms to change in temperature. The simplest approach to calculation of this relation is to find the relaxation volume of Al in Si. Nevertheless, after searching a few reliable and unreliable sources such as, some data bases and search engine, no data for relaxation of Al in Si was found. As a result of that, the relaxation volume of Al in Si was estimated by using the Al-Si bond length. Using the bond length for calculating the relaxation volume can be performed by estimating a spherical volume around Al and Si atoms with a radius equal to their bond lengths. This estimation requires exclusion of overlapping parts of the spheres. To exclude the overlapping parts, overall spherical volume of a certain number (here the number of Si atoms is equal to the Avogadro's number) of Si atoms, which was obtained by using Si-Si bond length, was divide by their actual volume to obtain a correction factor. (The Si-Si bond length used here is 235 pm.)

This correction factor was measured as 2.72 and it was used to connect the spherical volume approximation to actual volume of Al and Si atoms in a block of Si.

To check the reliability of this correction factor, it was used in microscopic level. As the volume occupied by a Si unit cell is known very precisely, see Figure 3, it could be used for checking the correction factor in microscopic level.

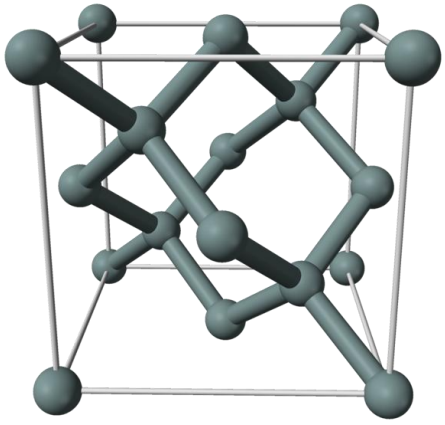

Figure 3: A conventional unit cell of Si [3].

A conventional unit cell of Si is made out of 18 Si atoms, see Figure 3, but overall only 8 atoms correspond to the volume of the unit cell. This is due to the fact that not all the atoms are completely inside a particular unit cell. For example, only 1/8 of each of the 8 atoms on the corners is inside the unit cell. The overall volume of this unit cell can be measured by using the lattice parameter of Si, which is 543 nm. This gives a volume of 1.601×10^{-28} m^3. This volume can be compared to the volume obtained by using the spherical volume approximation and the 2.72 correction factor.

$$\frac{4}{3}\pi(235\ \text{nm})^3 \times \frac{8}{2.72} = 1.599\times10^{-28}\ m^3$$

By comparing these two volumes, it can be concluded that the spherical volume approximation and the correction factor can be used for further volume approximations.

The next step for relating the number of Al atoms to change in the temperature was to find out what is the implantation of a single Al atom's effect on the volume of the Si block. By assuming that a single Si atom is substituted by a single Al atom and the Si atom travels to the top of the Si block, see Figure 4 in the next page, the spherical volume approximation can be used.

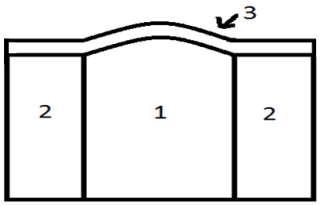

Figure 4: The side view of the Si block after implantation.

In Figure 4, part 1 shows the implantation region, parts 2 show the rest of the Si block and part 3 is the Si atoms which have travelled to the top of the Si block due to substitution of Si atoms with Al atoms.

The ratio between the number of Si atoms to Al atoms is 1000, which is a very high concentration for doping on scales greater than nano-scales, but this ratio for doping in nano-scale is about 10^4-10^3. Therefore, this used concentration is known as a high concentration. As a result of this ratio, the top layer of Si atoms, part 3 in Figure 4, can be neglected as the number of Si atoms in this layer is equal to the number of Al atoms and it is very small compared to the whole of the Si block.

By using the spherical approximation and neglecting the top Si layer, the change in volume due to substitution of one Al atom (ΔV_{SOA}) can be represented by the equation below.

$$\Delta V_{SOA} = \frac{4}{3\times 2.72}\pi\,(d^3_{Si\text{-}Al} - d^3_{Si\text{-}Si}) \qquad \text{Equation 1}$$

Where, d is the bond length between two atoms. (The Al-Si bond length used here is 248 pm, which corresponds to an increase in the volume due to implantation, as Si-Si bond length is 235 pm, as mentioned before.)

By multiplying ΔV_{SOA} by the number of Al atoms, the total change in volume due to implantation can be calculated.

Equation 1 multiplied by the number of Al atoms can be equated to a change in the volume of the central region of the Si block to find a relation between the number of Al atoms and change in temperature.

$$N_{Al}\,\Delta V_{SOA} = 3\alpha_{Si} V_o \Delta T \qquad \text{Equation 2}$$

Where, N_{Al} is the total number of Al atoms, V_o is the initial volume of the Si block and α_{Si} is the coefficient of thermal expansion of Si.

By rearranging Equation 2, a relation between change in temperature and the number of Al atoms can be found.

$$\Delta T = \frac{N_{Al}\Delta V_{SOA}}{3\alpha V_o} \qquad \text{Equation 3}$$

After obtaining a relation between the change in temperature and the number of Al atoms, the block could be simulated in COMSOL and the change in temperature could be applied by equating the coefficient of thermal expansion of the non-implantation region to zero, see Figure 5.

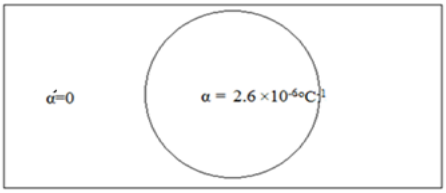

Figure 5: Top view of the silicon block, showing value of α for each part.

After applying the temperature change, and by importing the obtained data to a program designed in MATLAB by Ms. Xiaowen Shi the diffraction pattern of the Si block could be produced. An equation that is required for further analysis of the relation between the diffraction pattern and total displacements is shown below.

$$\phi = \mathbf{G}.\mathbf{u} \qquad \text{Equation 4}$$

Where, ϕ is the phase and **u** is the total displacement.

The value of ϕ greater than zero corresponds to the change in the diffraction pattern.

Results

By using the Avogadro's number and the density of Si, the total number of Si atoms inside the Si block shown in Figure 2 was calculated as 8.014×10^6. Therefore, for a concentration of 1 Al atom per 1000 Si atoms, the number of implanted Al atoms can be calculated. By using the number of Al atoms and Equation 3, the required change in temperature was calculated as 22k. This change in temperature was applied to the Si block designed in COMSOL, as described before, and Figure 6 in the next page shows a side view of this stained Si block. A top view of this block can be found in Appendix in page 28 as Figure A 1. This 22k change in temperature corresponds to a 1.97 nm maximum total displacement.

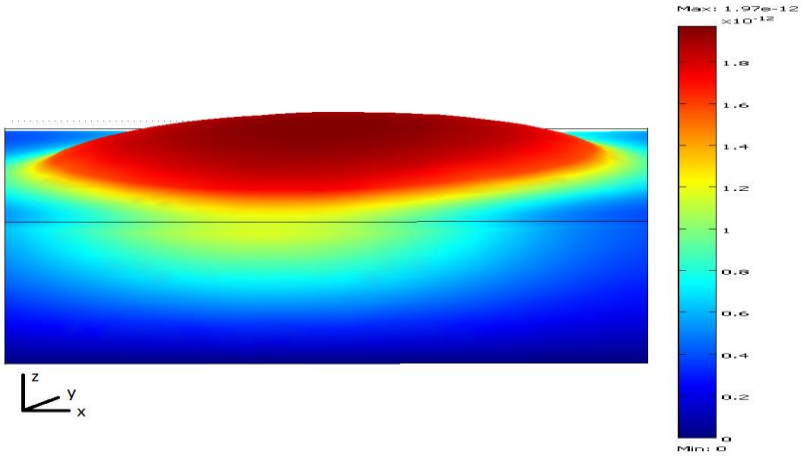

Figure 6: A side view of the strained Si block.

For further analysis, 110k and 220k change in temperatures were applied to see whether the change in temperature is linearly proportional to the maximum total displacement or not, and it was obtained that for this range of changes in temperature, there is a linear relation between the maximum total displacement and change in temperature.

The total displacements of this strained Si block were exported into the MATLAB program, explained before, to find the diffraction pattern of this Si block. However, no change in the diffraction pattern was obtained by using the imported total displacements and using Q (0 0 4), see Equation 4. Therefore, a very huge Q vector (about 750000 times the initial value of Q(0 0 4)) was used to increase the change in the diffraction pattern, and a great change, shown in Figure 7 was obtained.

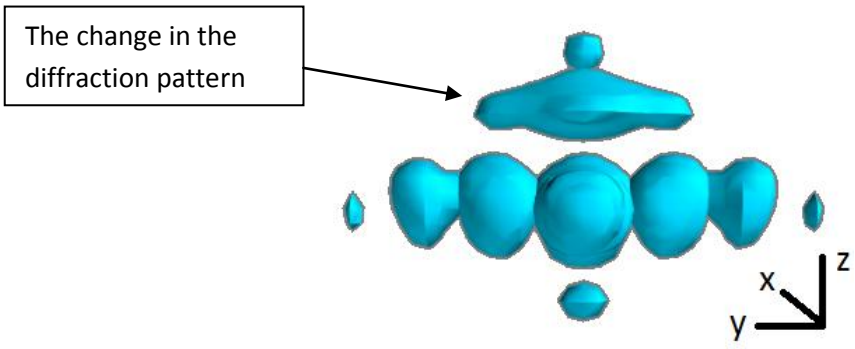

Figure 7: A huge change in the diffraction pattern of the Si block.

An attempt was made to find out what is the minimum ϕ that a change in the diffraction pattern can be seen. Therefore, ϕs obtained for the initial values of the total displacements and Q(0 0 4), where multiplied by 10 and 5, and a small change

could be seen for both, see Figure 8 for the diffraction pattern for 5ϕ and see Figure A 2 in Appendix page 28 for diffraction pattern for 10ϕ.

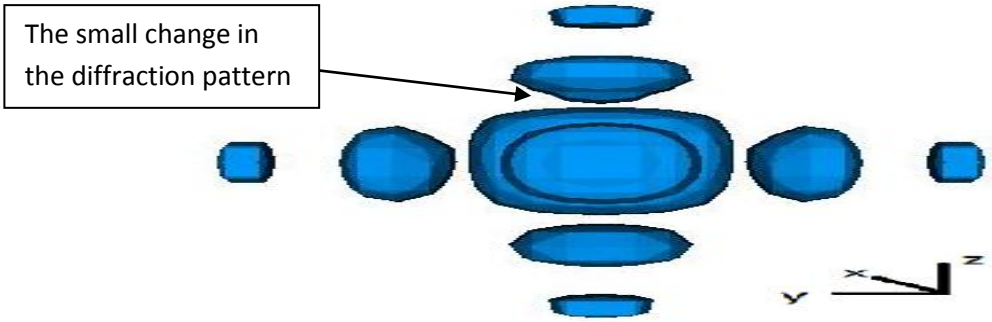

Figure 8: The diffraction pattern for 5ϕ.

Conclusion

In short, in this section an attempt was made to find the answer to the question "Is it possible to observe a change in diffraction pattern of a silicon block, as a result of strain due to implantation of aluminium into a block of Si". Therefore, a block of Si was designed in COMSOL to simulate the implantation of Al in the Si block by using thermal expansion. To achieve this simulation the number f Al atoms were related to a change in temperature, and for a 1 Al atom per 1000 Si atoms, 22k temperature difference was obtained. Then, this change in temperature was applied to the block of Si in COMSOL. Next, the total displacements where exported to a MATLAB program to find its diffraction pattern. The diffraction pattern showed a very small change for the phase values obtained initially multiplied by 5. These phase values can be obtained by increasing the dot product of Q vector and the total displacements by 5 times, see Equation 4. However, the used concentration of Al atoms in the Si block of 1 per 1000 is already a high concentration and higher concentrations may damage the crystal structure of the Si block. In addition, the Q vector used (i.e. Q (0 0 4)) is the maximum Q vector being practically available in London Centre for Nanotechnology. Therefore, it can be concluded that a change in the diffraction pattern, which is caused as a result of strain due to implantation of Al into Si, cannot be observed practically.

A recommendation for this section is to look up a more reliable value of the Al-Si bond length for more accurate measurement of the change in temperature.

One Day Trip to Diamond Light Source

A one day trip to Diamond Light Source was arranged by Prof. Ian Robinson as part of this project for familiarization to the experimental side of a project like this project. This experiment is similar to the theoretical measurement of the diffraction pattern in the previous section and it is described briefly in the following.

In this experiment, a sample of gold crystals covered with chromium was used, see Figure 9.

Figure 9: The sample used in the experiment in Diamond Light Source.

The sample was giong to be heated to about 300^{o}C to produce a Cr-Au alloy in the gold crystals by using a chamber shown in Figure 10, see Figure A 3 in Appendix page 28 for a picture of the chamber, ditached from the sample.

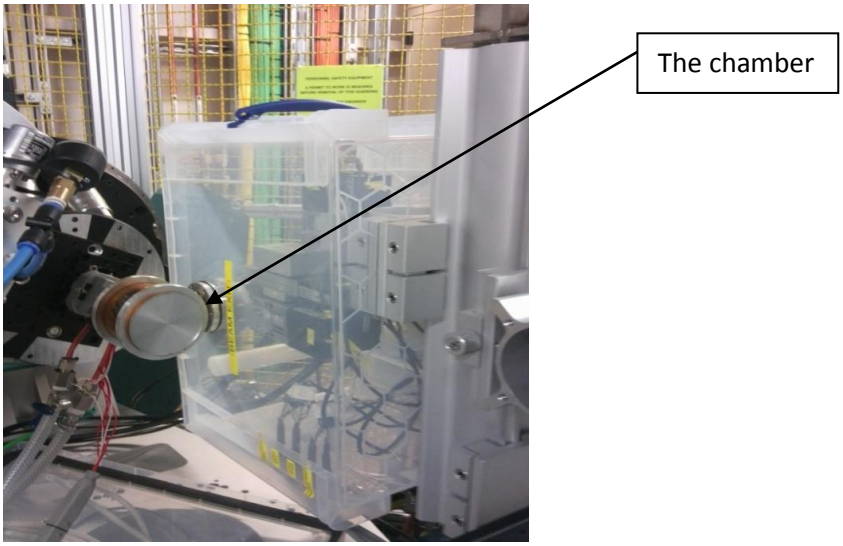

Figure 10: The chamber for heating the sample.

The main aim of this experiment was to obtain some diffraction patterns of this alloy, which is dependent on its properties, to find out if it could be beneficial in future or not. See Figure 11 for an example of the diffraxtion patterns, but this diffraction pattern was produced before heating the sample.

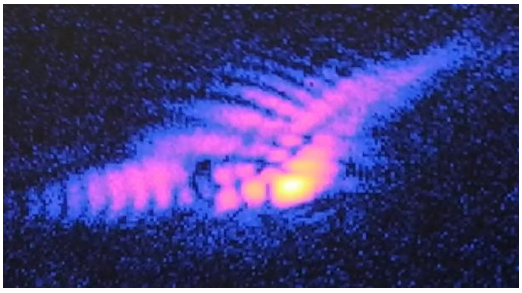

Figure 11: Diffraction pattern of a gold crystal before heating the sample.

The diffraction pattern of this sample could be obtained by emitting X-ray beam on the sample and detecting the diffraction pattern by a detector, see Figures A 4 and A 5 for pictures of the vacuum chamber of the X-ray beam and the detector respectively in the Appendix page 29.

Some conditions, such as, the incident angle, the possition of the sample and the intensity of the X-ray beam, could be varied inside a control room, see Fiure 12. For a picture of the mechanism, which was used to control the incident angle and the possition of the sample, see Figure A 6 in Apendix page 29, and for a picture of the filters used for changing the intensity of the beam, see Figure A 7 in Appendix page 29.

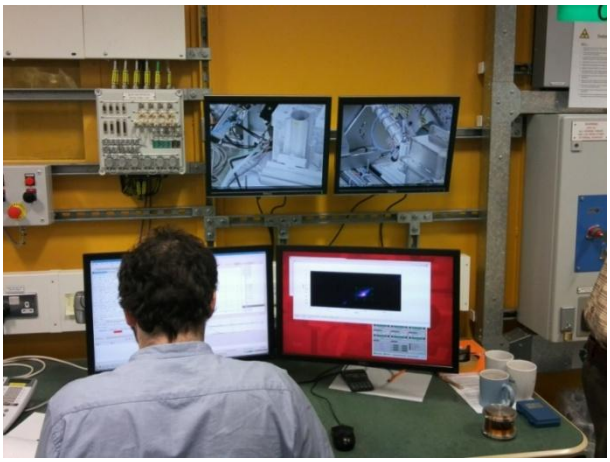

Figure 12: A picture of the control room.

If theoretically it was possible to observe the change in the diffraction pattern of the Si block, which was described in the previous section, such experiments could be performed to experimentally observe the change in the diffraction pattern.

Strain in a Block of Silicon due to Relaxation of SSOI

Introduction and Backgound

This section is about relaxation of Strained Silicon On Insulator (SSOI).

This SSOI can be produced in three main steps. Firstly, a block of Si with surface area of 20 x 20 microns and height of about 300 microns can be bombarded with oxygen atoms or heated up to produce a layer of SiO_2 on top of the Si block with a height of about 1 micron to produce an insulator. Next, another layer of Si with the same surface area can be mounted on a block of GeSi. As GeSi has a lattice parameter of slightly larger (about 0.6%) than the lattice parameter of Si, the Si block on top of the GeSi becomes strained to keep the same lattice parameter as the lattice parameter for the GeSi. Finally, by placing the Si on top of the SiO_2, see Figure 13, and polishing the GeSi away, the SSOI can be produced.

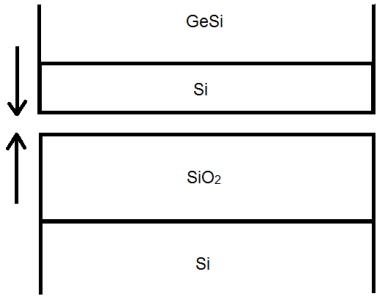

Figure 13: Placing a block of strained Si on top of SiO_2.

By cutting the Si wafer into a 1 x 1 micron Si device, the strained Si tries to return to its original structure, which requires reducing its lattice parameter by 0.6%. This fact is called relaxation of SSOI. Not very precise cutting of the strained Si block can result in cutting different heights of SiO_2 excess below the Si device, see Figure 14.

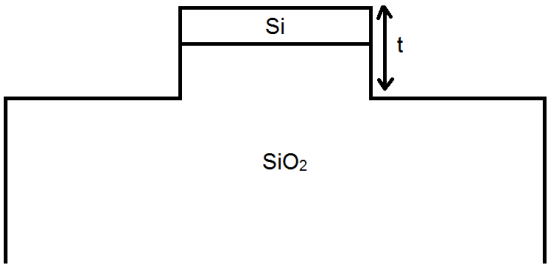

Figure 14: SiO_2 excess below the Si device (t = height of Si device + SiO_2 excess).

Different heights of the SiO_2 excess can result in different displacement fields inside the Si device. In this section, the relation between different thicknesses of the Si and SiO_2 excess (t) and the displacement fields, which are mainly the displacement fields in one direction on top of the Si device, are going to be studied. After finding a relation between t and the displacement fields, t is going to be estimated for a real sample.

Methods

To look at the displacement fields a block of Si can be simulated in COMSOL, see Figure 15. The height of the Si device is considered 20 nm for all the measurement for this section.

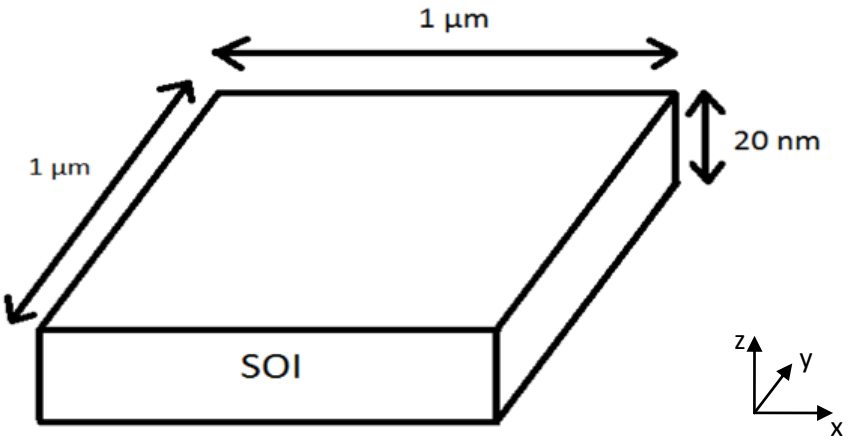

Figure 15: The dimensions of the Si device.

For different heights of the SiO_2 excess another block with the same surface dimensions as the Si device can be designed below this Si device with different desired heights. The values of t, which are planned to be studied in this project, are 20, 40, 70, 120, 520, 820 nm.

For the insulator part, which is the 20 x 20 microns SiO_2, the base of the Si device could be fixed or a fixed block of SiO_2 could be designed, these two methods do not differ as the base of the Si device is fixed in both cases.

To apply the strain inside the Si device, a function, designed in COMSOL, can be used, which is called initial strain. Therefore, by using this function, 0.6% initial strain should be applied in xx and yy, to have a similar effect to the relaxation of the SSOI. In addition, this relaxation effect can be simulated by using thermal expansion again.

Therefore, by using thermal expansion a change in temperature can be fund to achieve the same displacement field as the displacement field calculated by the initial strain function for one specific t value. Then, by applying the same temperature difference to other values of t, the effect of the initial strain can be compared with the effect of the temperature difference for checking the reliability of both.

As described before, in this project, the effects of the relaxation of the SSOI were planned to be studied. Therefore, the displacements in x and z-directions, see Figure 15, as a function of x were decided to be investigated, which correspond to the top surface of the Si device. In addition to the x and z displacement fields, the maximum displacements in x-direction and λ were considered to be studied as a function of t. In this project, the value of λ represents a point on the x-axis, where the displacements are e^{-1} times the maximum displacements in x-direction. This positions is called λ as it was predicted that the displacements in x-direction as a function of x can be explained by an exponential function in a form of $ae^{-x/\lambda}$, where "a" is the maximum displacement in x-direction.

Results

A block of Si with dimensions shown in Figure 15 was simulated in COMSOL on top of SiO_2 excess, which where mounted on a SiO_2 block with dimensions mentioned before. Then, initial strain was applied to the designs with different values of t, mentioned before. See Figures 16 to 18 for the x displacement fields for t values of 20, 70 and 820 nm and see Figures 8 to 10 in Appendix page 30 for x displacement fields for other values of t.

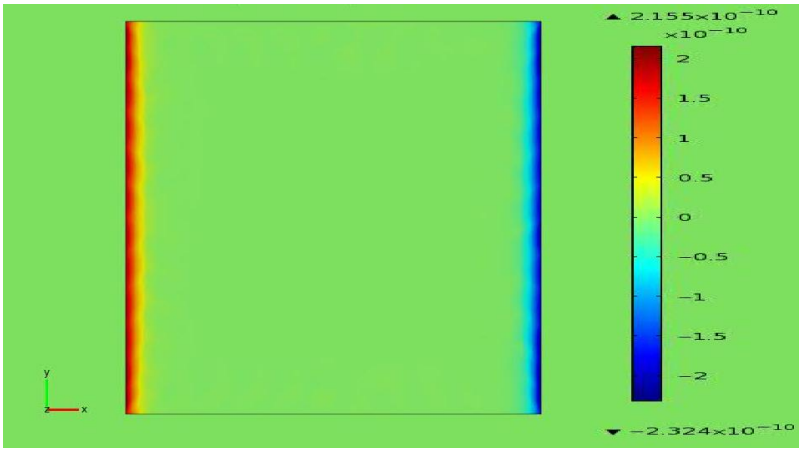

Figure 16: The x displacement field for t = 20 nm, by applying initial strain.

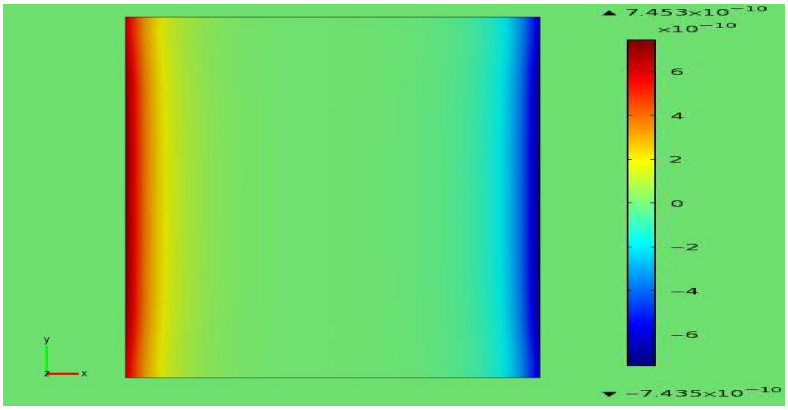

Figure 17: The x displacement field for t = 70 nm, by applying initial strain.

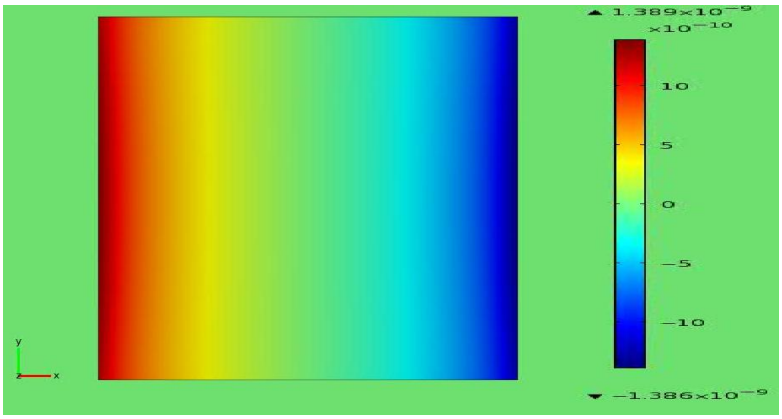

Figure 18: The x displacement field for t = 820 nm, by applying initial strain.

By reducing the temperature by 1446k on the Si device only in COMSOL for t = 20 nm, a x displacement field was achieved, which was similar to the x displacement field shown in Figure 16, which was found by using the initial strain function in COMSOL. Then, the same change in temperature was applied to other designs with other values of t, which were similar to t values explained before. The x displacement fields for t = 20, 70 and 820 nm are shown in Figures 19 to 21 in order.

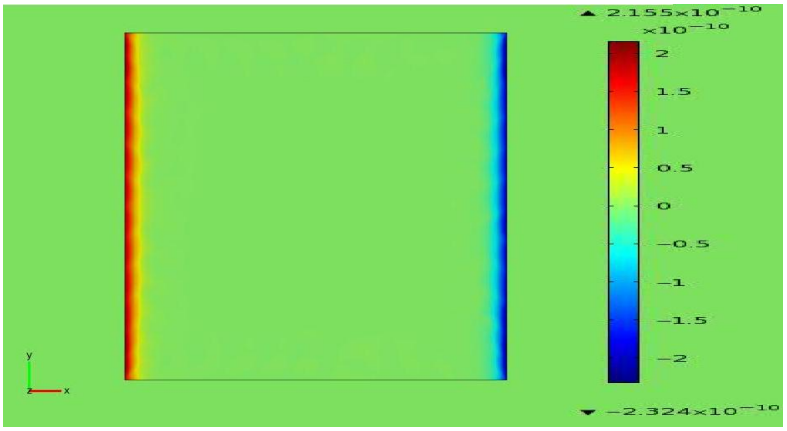

Figure 19: The x displacement field for t = 20 nm, by using change in temperature.

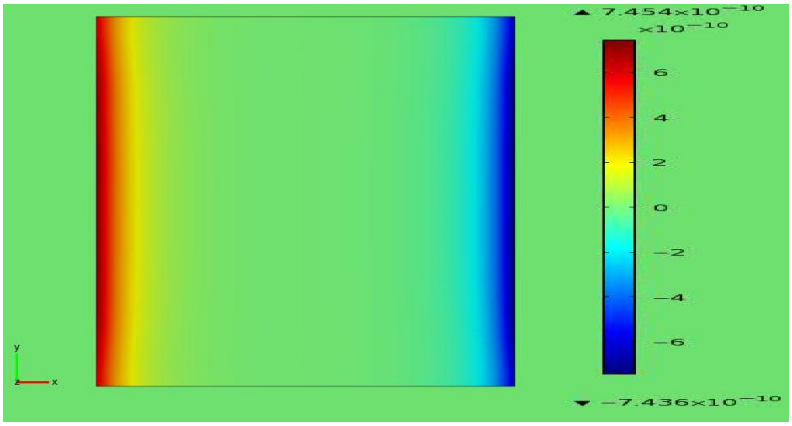

Figure 20: The x displacement field for t = 70 nm, by using change in temperature.

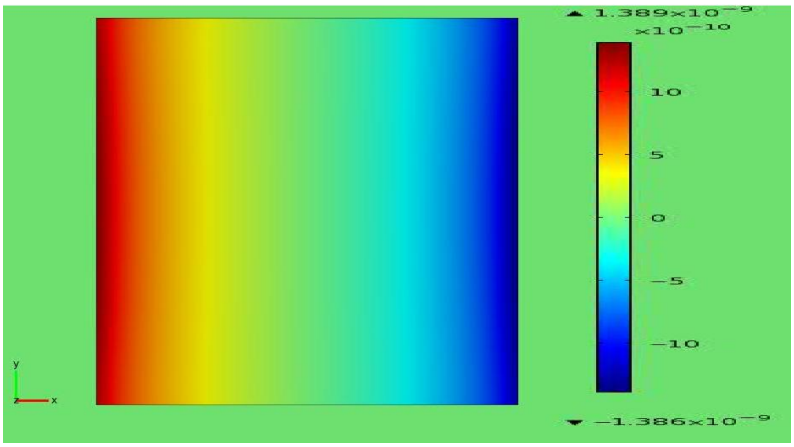

Figure 21: The x displacement field for t = 820 nm, by using change in temperature.

Next, the displacements in x (u_x) and z (u_z) directions Vs x, and u_{max} and λ Vs t could be plotted by using the data obtained before.

By exporting the x displacement values as a function of x into Microsoft Excel for half the Si device in x direction (as the other half is completely symmetric), an exponential function could be fitted into the data by using the trendline function in Microsoft Excel for small values of t (i.e. t = 20, 40 and 70 nm), see Figure 22 for u_x Vs x for t = 70 nm. However, for the remaining t values an exponential function could not be fitted into the data, see Figure 23 for u_x Vs x for t = 120 nm. In this project the main functions that are fitted into the data are exponential or logarithmic as Poisson equations for explaining the behaviour of stress in materials are mainly exponential or sinusoidal.

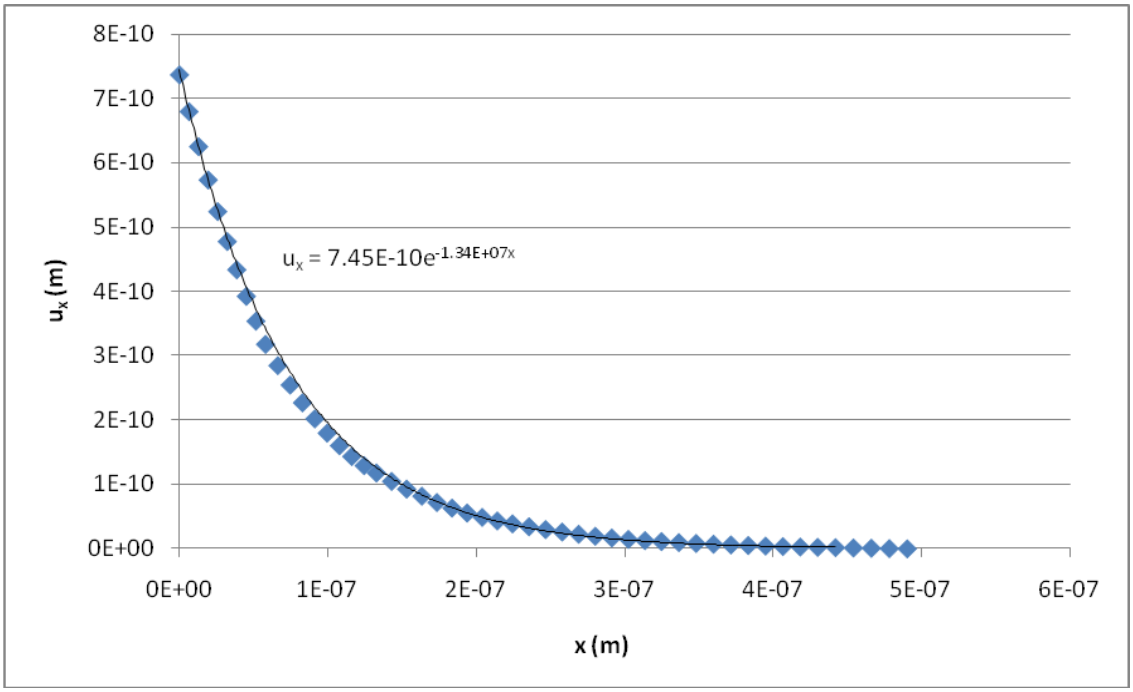

Figure 22: u_x Vs x for t = 70 nm.

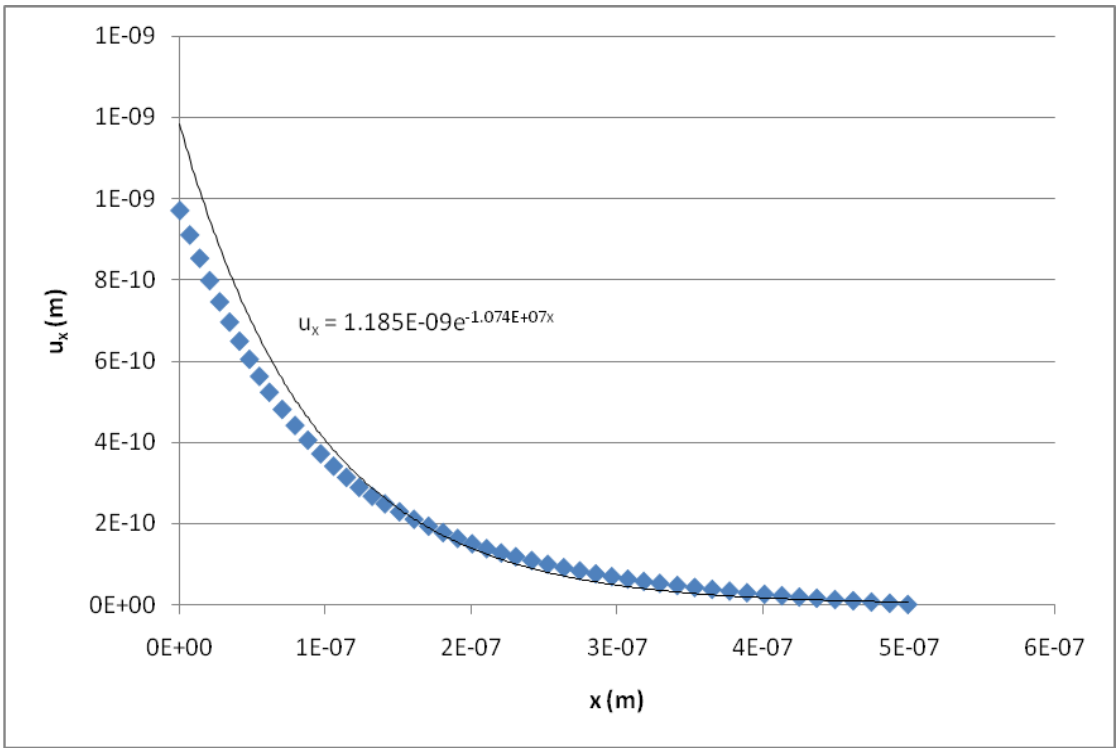

Figure 23: u_x Vs x for t = 120 nm.

For the z displacements as a function of x, the data for t = 70 nm was plotted in COMSOL itself and it was not exported for function fitting, as no specific function

could be considered for fitting into the obtained data, see Figure 24 for u_z Vs x for t = 70 nm.

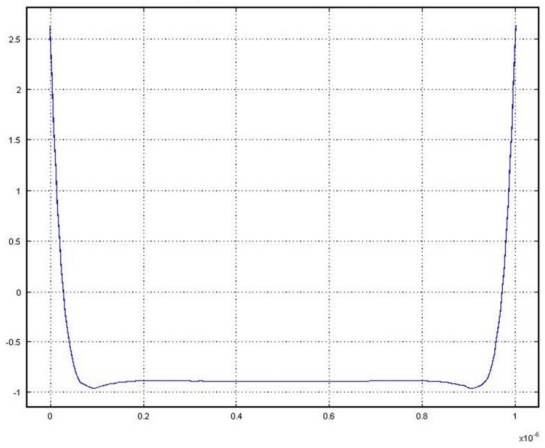

Figure 24: u_z Vs x for t = 70 nm.

In addition to the displacements as a function of x, the maximum displacements and λ as a function of t were plotted and logarithmic and arctan functions were attempted to be fitted into the data, see Figures 25 and 26. In Figure 26 the values of λ are calculated by using exponential functions, which were derived by fitting an exponential function in the u_x Vs x graphs for t = 20, 40 and 70 nm. However, for t = 120 nm, 520 nm and 820 nm, it is estimated as the position on x-axis, where the displacements are 0.37 (i.e. about e^{-1}) times the maximum displacements by using the u_x Vs x data exported from COMSOL.

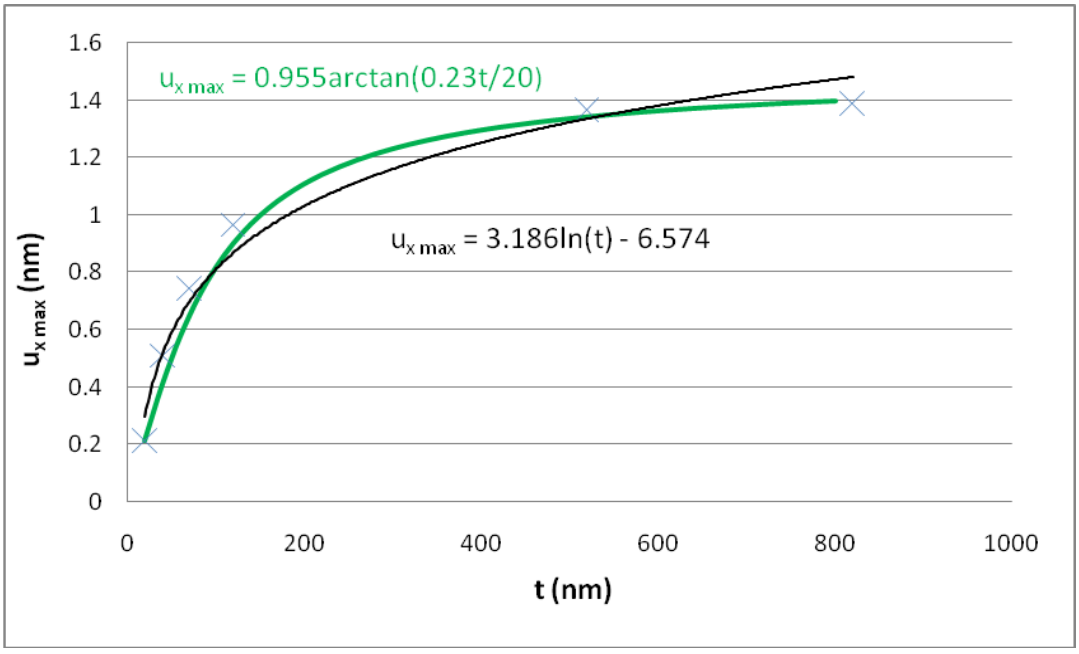

Figure 25: $u_{x\,max}$ Vs t.

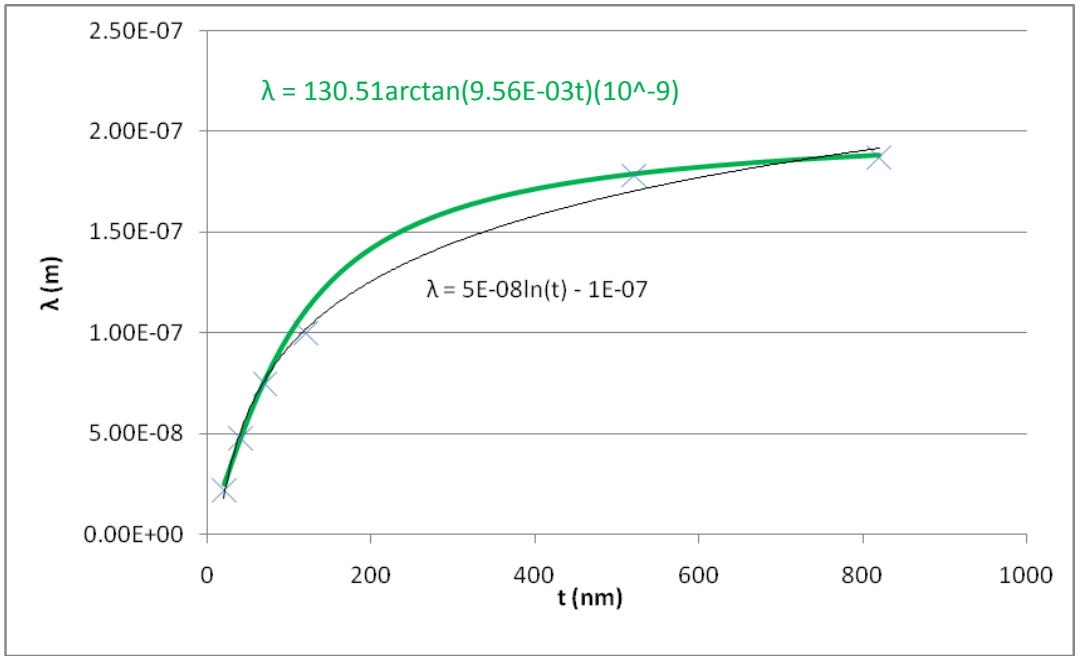

Figure 26: λ Vs t.

Next, the data obtained was used to estimate the t value for a real sample, which was produced by Oussama Moutanabbir in Max Planck Institute of Microstructure Physics in Germany. (The real sample data could not be used for comparison, as the t value is not measured for it.)

By using Equation 4, Figure 27, which is produced by Dr. Gang Xiong and Dr. Xiaojing Huang, and the legend for Figure 27, see Figure A 11 in Appendix page 30, the value of the $u_{x\,max}$ could be estimated as 0.05 nm, and the value of λ was estimated at about 90 nm.

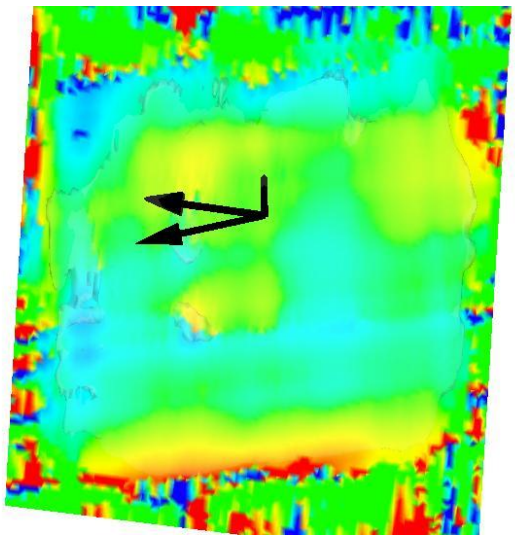

Figure 26: λ Vs t.

As the value of $u_{x\,max}$ is even smaller than the $u_{x\,max}$ for Si device with no SiO_2 excess, see Figure 16, λ was used to estimate the value of t for the real sample. The small value of $u_{x\,max}$ could be caused as a result of damaged edges of the Si device due to cutting of the SSOI into 1 x 1 micron. By using the logarithmic function, which appears to explain the behaviour of λ Vs t better for small values of λ, the t value for the real sample can be estimated as 93 nm, which corresponds to 73 nm of SiO_2 excess.

Conclusion

In short, the effects of relaxation of SSOI for different heights of the SiO_2 excess below the Si device were studied.

By using a built in function in COMSOL, called initial strain, relaxation of SSOI for different heights of the SiO_2 excess were simulated. As it can be seen from Figures 16 to 18, change in the height of the SiO_2 excess can vary the displacement field on top of the Si device dramatically.

Next, thermal expansion was used to simulate the relaxation of the SSOI, which could help to check the reliability of the obtained data. By comparing Figures 16 to 18 by Figures 19 to 21, it can be concluded that the obtained displacement field by thermal expansion are exactly similar to the displacement fields found by using initial strain, see Figure 27 for t = 70 nm.

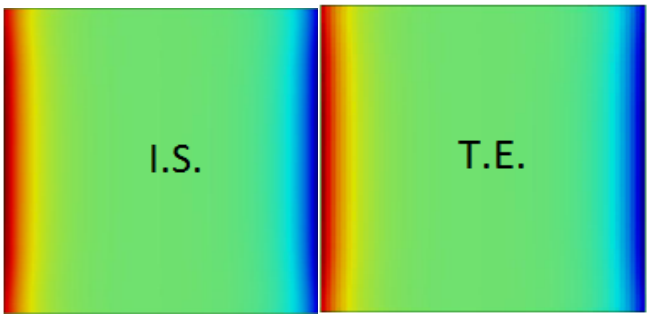

Figure 27: Comparing the displacement fields found by T.E. and I.S. for t = 70 nm.

To achieve this similarity 1446k change in temperature was required. This may not be practically possible to achieve, as the melting point of Si is 1687k [(4)], and by getting close to the melting point the structure of Si may vary dramatically, and may not obey the previous behaviours anymore. However, the reason, why this could be

achieved by using COMSOL, is probably because of proportionality of change in temperature and strain in COMSOL.

In addition, u_x and u_z Vs x were studied. For small values of t, u_x Vs x could be explained by using an exponential function, which was expected, as explained before, but for greater values of t, the exponential behaviour is not perfect, which could be as a result of other factors contributing to the x displacements, which cannot be explained in this project. In addition, no function could be found to explain the behaviour of u_z Vs x.

Moreover, a logarithmic function and an arctan function were used to explain the trend of the maximum displacements Vs t, see Figure 25. However, neither of them could be fitted into all the obtained data perfectly. Nevertheless, the arctan function could explain the overall trend of the data, and a better calculation of data by using a finer mesh in COMSOL could result in obtaining a function that explains the behaviour better.

Furthermore, the logarithmic function, which was used, could explain the trend of λ Vs t for small values of t. However, the arctan function could pass through all the data fairly well, excluding the value of λ at t = 120 nm. This could be as a result of the fact that the values of λ are not measured perfectly and a more exact calculation of λ requires a finer mesh to be used in COMSOL.

Finally, t value for a real sample was estimated at 93 nm, by using the logarithmic function found.

A recommendation for this section is using a finer mesh for producing the displacement fields in COMSOL for more precise measurement of the further values. The meshes used in this project were mainly “normal” size, which is how it is described in COMSOL.

Reference List

1. Wikipedia.org, modified on 6 March 2011, retrieved on March 2011 from http://en.wikipedia.org/wiki/32_nanometer

2. Edited and retrieved from http://www.click4chill.com/wp-content/uploads/2010/07/periodic_table.gif

3. Wikipedia.org, retrieved on March 2011 from http://en.wikipedia.org/wiki/File:Silicon-unit-cell-3D-balls.png

4. Wikipedia.org, modified on 17 March 2011, retrieved on March 2011 from http://en.wikipedia.org/wiki/Silicon

Appendix

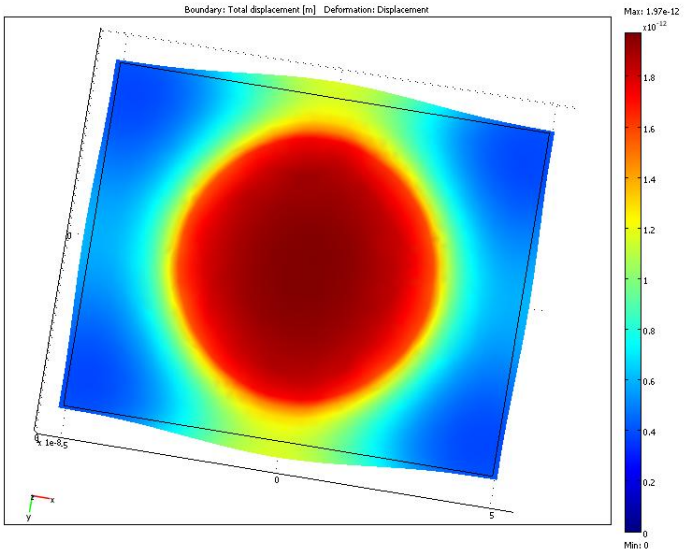

Figure A 1: The top view of the strained Si block.

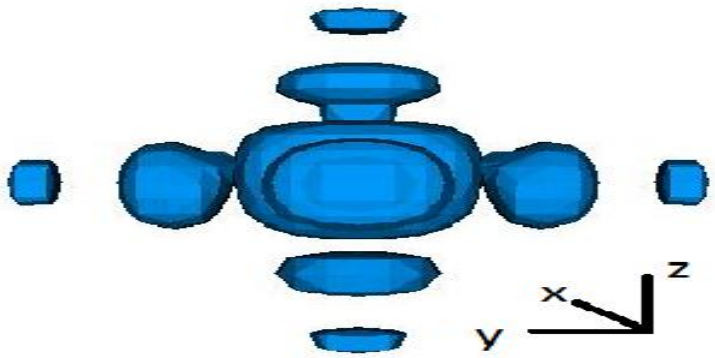

Figure A 2: The diffraction pattern for 10ϕ.

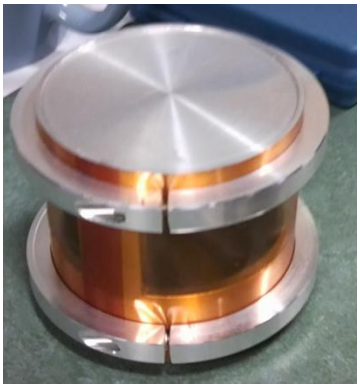

Figure A 3: The detached chamber for heating the gold sample.

Figure A 4: The vacuum chamber of the X-ray beam

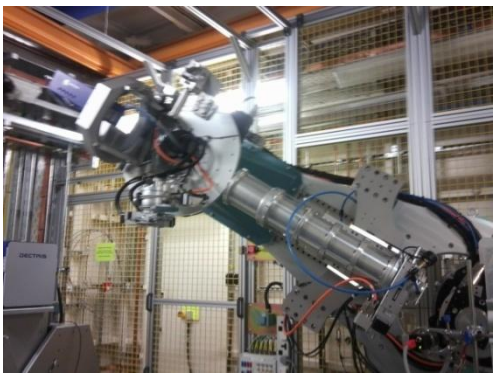

Figure A 5: The detector, which is the blue box in the top left corner.

Figure A 6: The mechanism for changing the incident angle and position of sample.

Figure A 7: The filters for reducing the beam's intensity.

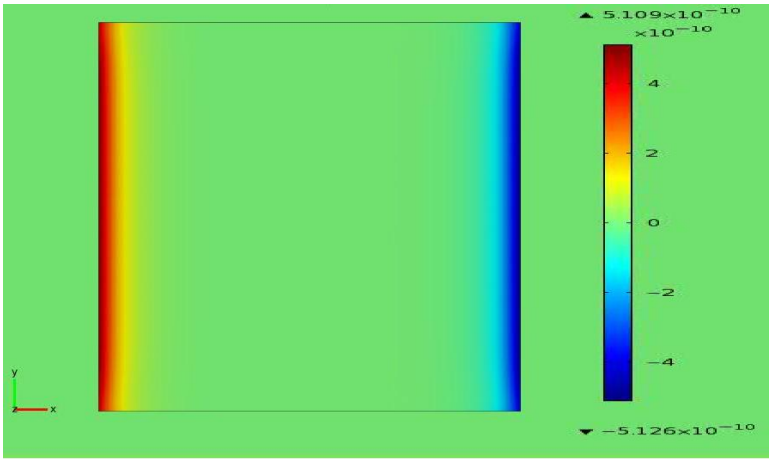

Figure A 8: The x displacement field for t = 40 nm, by applying initial strain.

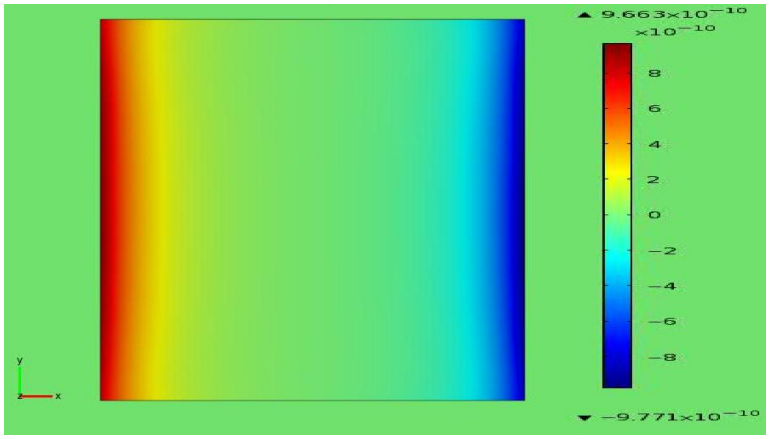

Figure A 9: The x displacement field for t = 120 nm, by applying initial strain.

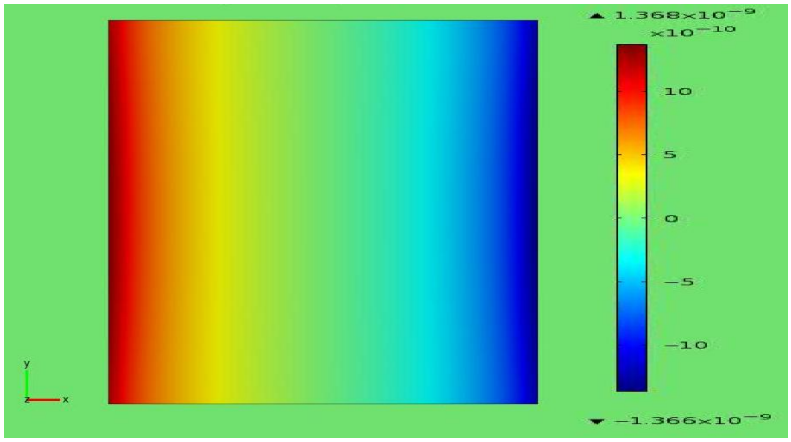

Figure A 10: The x displacement field for t = 520 nm, by applying initial strain.

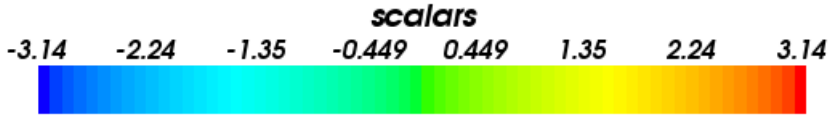

Figure A 11: The legend for Figure 27.