Dynamic Simulation of Solid Silicon Nanoneedle for Cell Surgery

M. W. Ashraf, S. Tayyaba, H. Rasheed, M. S. Khan, S. M. Rana, A. Jalbani and N. Afzulpurkar

Abstract—**Atomic force microscopy (AFM) is one of the attractive way to manipulate the single cell. AFM based manipulation in the biomedical is increasing day by day, especially for cell and tissue handling. Here authors present the design, simulation and dynamic analysis of silicon based solid nano needle connected with silicon nitride AFM cantilever. Solid nano needle with square base has been designed on the tip of flexible cantilever. The needle length is 10 µm and tip diameter is 250 nm. The diameter of needle base is 10^3 nm. Semi sphere hypo elastic single cell is designed for puncturing. The diameter of cell model is 50 µm. ANSYS workbench module has been used to perform the dynamic analysis. The mechanical properties of device and failure were investigated during the cell surgery. Axial and transverse forces were pertained on the needle connected with cantilever to envisage the bending and stress distribution. This presented data would be useful to develop the nano manipulator for single cell surgery.**

Index Terms—**Cell Surgery, Computer Simulation, Dynamic Analysis Solid Nanoneedle,**

I. INTRODUCTION

Micro/Nano devices have shown impending applications in biomedical field. The plausible medical applications of Micro and Nano Electromechanical System (MEMS, NEMS) based technologies are: drug delivery, nano surgery, drug synthesis, nano therapy, diagnostics, biocompatible structures and materials, disease detection and prevention [1]. Based on these technologies, the development and fabrication of diminutive dimension and high performance devices has become probable to convene crucial medicinal and therapeutic requirements [2]. The treatment of cell is the vital technology for biomedicine and analytical systems. The precise and accurate progression to manipulate the living cell is the main requirement for deep and close envision of the cell performance and actions.

The atomic force microscopy has been employed significantly for cell biology in recent years. There is a lot of involvement of microscopic methods to the systematic advancement in biomedicine, biology and material science [3]. The Atomic Force Microscope (AFM) has a cantilever with a nanoneedle at one corner. Nanoneedles have been used to penetrate the living cell to reach the nucleus, insert molecules and conduct cell manipulation. The location of the needle can be controlled precisely by examining the exerted force. The tip of cantilever should be very pointed, emaciated and robust to get into all the split and corners of the section without any fracture by bearing all the forces applied on it. A number of materials have been used to develop various shapes of needle for different applications and uses [4]. A new process has been reported for single cell surgery by means of rigid nanoneedle. The finite element model of rigid nanoneedle was developed. The yeast cell was taken for processing while the needle was based on Tungsten material [5]. A number of researchers have done efforts to develop the enhanced and improved tip for precise and exact outcomes. Nano needles based on Zinc oxide (ZnO) were developed through the thermal oxidation processing of untainted zinc [6]. The silicon based nanoneedle was inserted into living melanocyte and mechanical reactions were analyzed through the AFM. It was observed that the mechanical reactions were dependent on the contour of the nanoneedle used for penetration into living cell [7]. The yeast cells had been used for the investigation process to analyze the cellular mechanics within the environmental SEM (ESEM) [8]. The robustness of nano needle with tapered shape was analyzed and it was observed that tapered nanoneedle showed good results of robustness than cylindrical nanoneedle. The tapered nanoneedle was inserted into living cell using AFM [9]. The direct imaging of cellular bending and restructuring was performed through an instrument. The fabrication and development of arrays and films of nanoneedles made of ZnO was done. The process of anodic etching was employed for the fabrication of nanoneedle [10]. The AFM and side view fluorescent imaging were employed for the proposed instrument [11]. The fabrication of arrays of nanoneedles using reactive ion etching has been presented [12].

The new progress and potential trends of the nanoneedle technology have been evaluated for biological analysis of living cells [13]. The nanoneedles have been employed for the mechanical tomography of human corneocytes to identify and envisage the biomechanical transformation in corneocytes due to several aspects like dermatological pathologies, aging and environmental problems [14]. The synthesis of nanoneedles for the applications of glucose sensing has been presented. The 3D nickel cobalt oxide nanoneedles have been synthesized on nickel foam. The

M. W. Ashraf, Department of Physics (Electronics), GCU Lahore, Pakistan, S. Tayyaba, Computer Engineering Department, The University of Lahore, Pakistan, H. Rasheed, Electrical Engineering Departmen, Bahria University Karachi, Pakistan, M. S. Khan, NCB&E, DHA Campus, Lahore, Pakistan. S. M. Rana, Institute of Electronics, Atomic Energy Research Establishment, Bangladesh Atomic Energy Commission, Bangladesh, A. Jalbani, Computer Science Department, QUEST, Nawabshah, Pakistan, N. Afzulpurkar, AIT, Bangkok, Thailand. Email: Muhammad.Waseem.Ashraf@gmail.com.

nanoneedles have been proposed to present high impending for the detection of glucose in food products, living cell based samples and further relevant fields [15]. The fabrication of nanoneedle structured thin film has been presented for Transparent Conductive Oxides (TCO) applications [16].

In this work authors presented extended work of their paper of NCMCS 2015. They presented the design, simulation and analysis of AFM cantilever tip based solid nano needle for single cell surgery. Silicon (Si) material has been selected for solid nanoneedle while silicon nitride (SiN) has been considered as the material for cantilever beam. Dynamic analysis was performed by making spherical single cell. Hyperelastic properties of spherical cell were considered during simulation and skin puncturing was observed.

II. THEORETICAL ANALYSIS

The mechanical and structural properties of needle and cantilever are very important constraints for proper insertion into living cell. There are some significant parameters of the device that should be considered like bending, deflection, stress, strain and buckling force. To observe the performance of cantilever and needle bending to puncture the single cell, the correlation of deflection and stress are crucial. The AFM cantilever spring constant is an important parameter and can be measured by equation (1).

$$k = \frac{WEt^3}{4L^3} \qquad (1)$$

Where, K represents spring constant, W represents the width of cantilever, E represents the young modulus and L represents the length of cantilever beam.

The Stoney formula can be used to calculate the deflection of the cantilever as shown in equation (2).

$$D = \frac{C\sigma(1-\upsilon)}{E}\left(\frac{L^2}{t^2}\right) \qquad (2)$$

Where, D represents the deflection in cantilever beam, σ represents the stress on cantilever beam, υ represents the Poison ratio, E represents the young modulus, L represents the beam length and t represents the beam thickness.

Buckling of the nanoneedle is another significant constraint that should be observed through the process of single cell puncturing. The Euler equation can be employed to measure the buckling force as shown in equation (3).

$$F_{Buckling} = \frac{EI\pi^2}{KL^2} \qquad (3)$$

Where, E represents the young modulus, I represents the moment of inertia. The moment of inertia can be calculated by using the relation given in equation (4).

$$I = \frac{\pi d}{64} \qquad (4)$$

Where, d represents the needle diameter.

III. NUMERICAL SIMULATION

ANSYS workbench was used for dynamic analysis of nano solid needle attached with AFM cantilever. This analysis was performed to study the bending of needle, bending of beam, stress on needle, stress on beam and deformation. First, 3D model of square based needle was designed and glued with 3D model of designed AFM cantilever. The needle length is 10 µm and tip diameter is 250 nm. The diameter of needle base is 10^3 nm. Semi sphere hypo elastic single cell is design for puncturing. The diameter of cell model is 50 µm. Then material properties of silicon and silicon nitride were defined for needle and beam. Then the 3D geometry was meshed as shown in Fig.1.

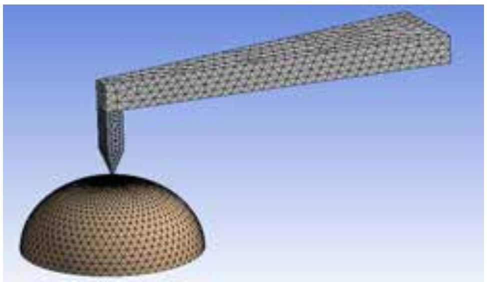

Fig. 1. 3D mesh model.

Then boundary conditions were defined. Axial and transverse forces were applied on needle tip. These forces allow the needle to move to and fro and up down. The material properties for silicon nanoneedle are shown in Table 1.

TABLE 1
MATERIAL PROPERTIES

Properties	***Values***
Poison ratio	0.24
Young modulus (GPa)	169
Density (kg/m^3)	2329
Bulk Modulus (Pa)	7.49 e^{11}
Shear Modulus (Pa)	4.71 e^{11}

Axial load (force) from 10 mN to 100 mN has been applied on the needle to foresee the bending and stress distribution in ANSYS workbench module as shown in Fig. 2, Fig. 3, Fig. 4, Fig. 5 and Fig. 6 at different time steps in dynamic transient analysis.

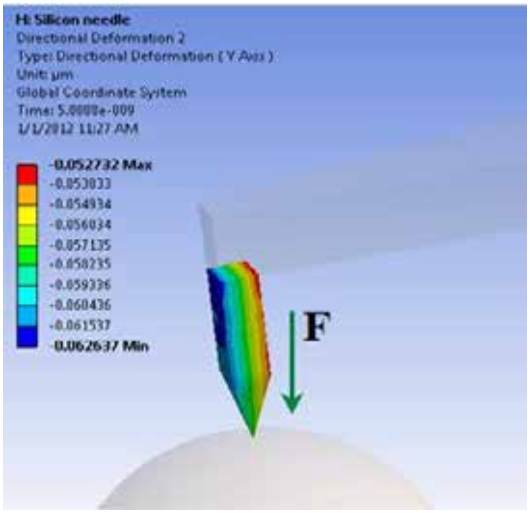

Fig. 2. Deformation due to axial load when needle touch the cell.

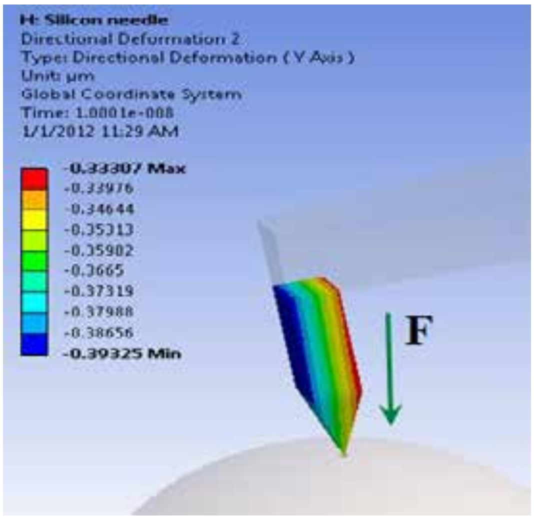

Fig. 3. Deformation due to axial load when needle start puncturing outer layer.

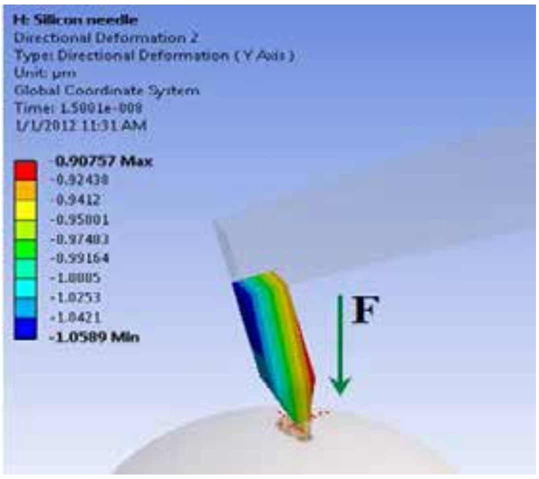

Fig. 4. Deformation due to axial load when needle puncture outer layer of cell.

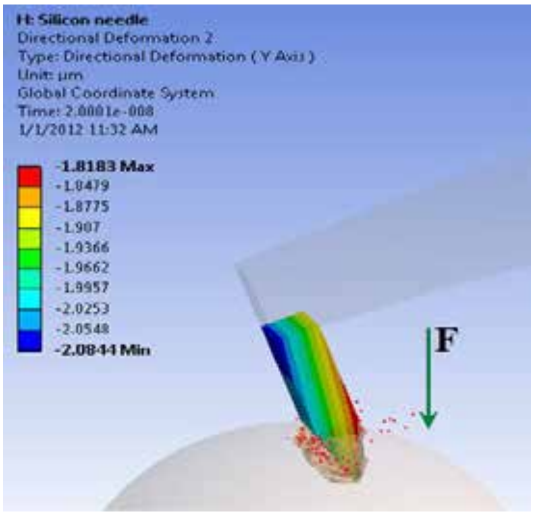

Fig. 5. Deformation due to axial load when needle puncture inner layer of cell.

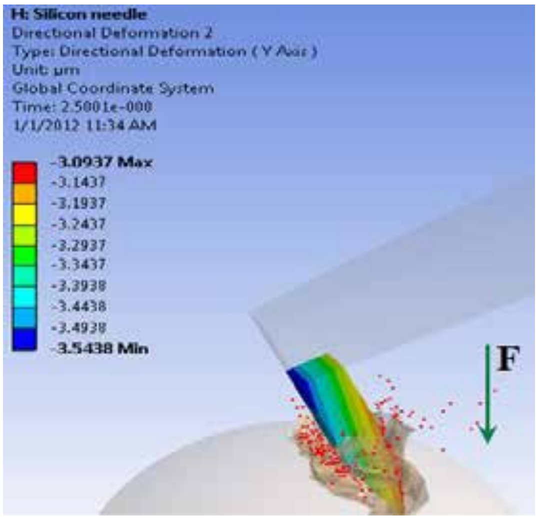

Fig. 6. Deformation due to axial load when needle reached inside cell.

Simulation results shows that the deformation of 0.05 µm, 0.33 µm and 0.9 µm have been observed when the nanoneedle touch the cell, start puncturing and completely puncture the outer layer of cell at first, second and third time step respectively. The bending of cantilever and insertion of nanoneedle increases with the applied load linearly. In axial analysis, the nanoneedle moves in vertical direction and operates in deeper areas.

In transverse analysis, transverse load (force) from 0.1 mN to 5 mN has been applied on the needle to predict the bending and stress distribution in ANSYS workbench module as shown in Fig. 7, Fig. 8, Fig. 9, Fig. 10 and Fig. 11. It has been observed that the low forces are required for cell manipulation. In transverse analysis, nanoneedle moves in horizontal direction and increase the insertion area horizontally.

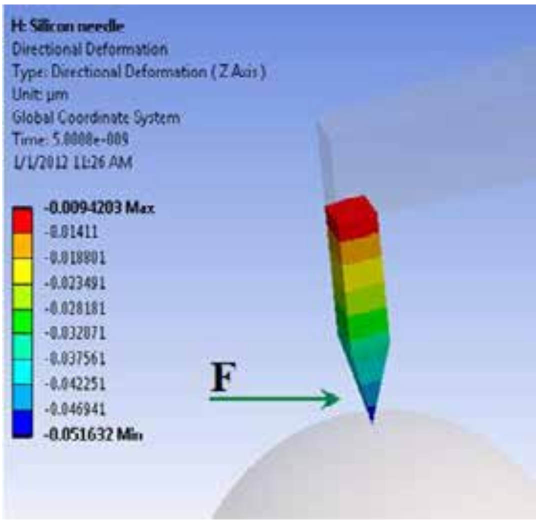

Fig. 7. Deformation due to transverse load when needle touch the cell.

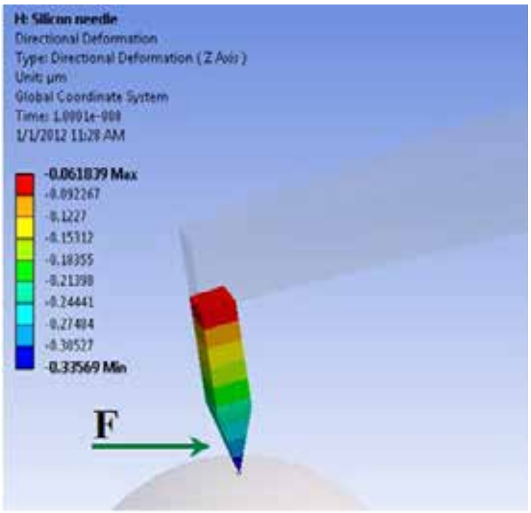

Fig. 8. Deformation due to transverse load when needle start puncturing outer layer.

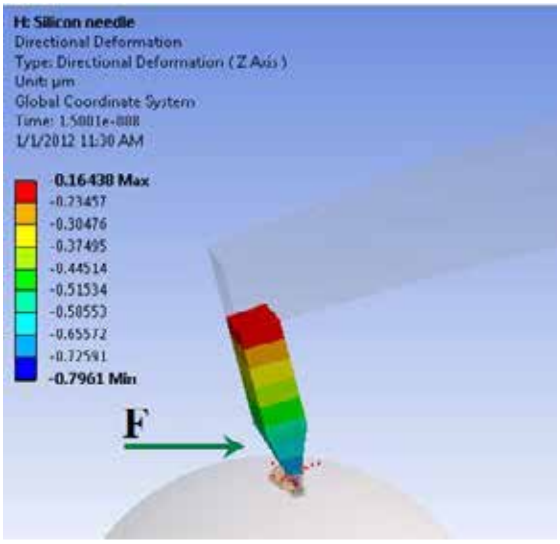

Fig. 9. Deformation due to transverse load when needle puncture outer layer of cell.

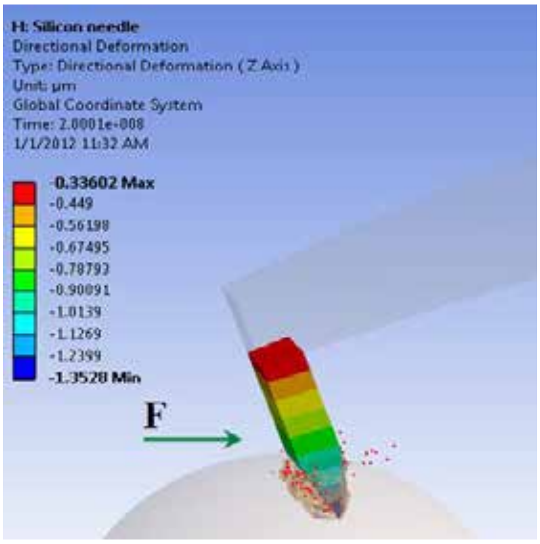

Fig. 10. Deformation due to transverse load when needle puncture inner layer of cell.

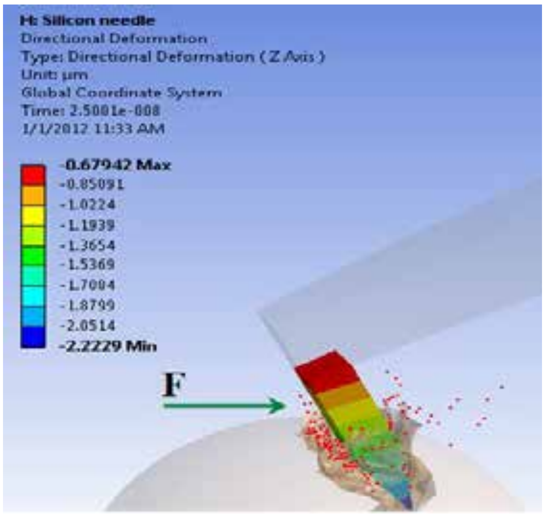

Fig. 11. Deformation due to transverse load when needle reached inside cell.

Simulation results shows that the deformation of 0.009 µm, 0.06 µm and 0.16 µm due to transverse load have been observed when the nanoneedle touch the cell, start puncturing and completely puncture the outer layer of cell at first, second and third time step respectively.

The stress distribution in Si nanoneedle at applied load is shown in Fig. 12, Fig. 13, Fig. 14, Fig. 15 and Fig. 16. The simulation results show that the stress value is below the yields strength of the material.

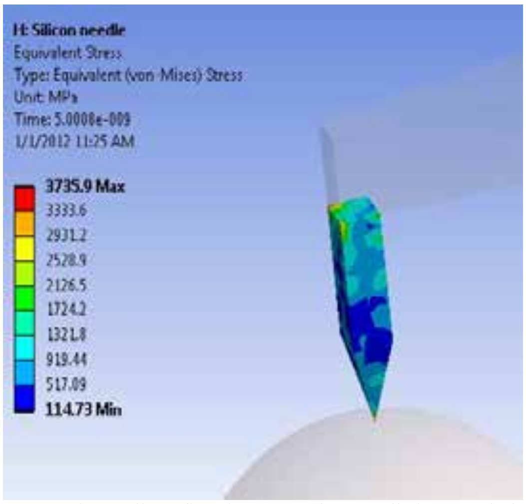

Fig. 12. Stress in needle at first time step when needle just touch the cell.

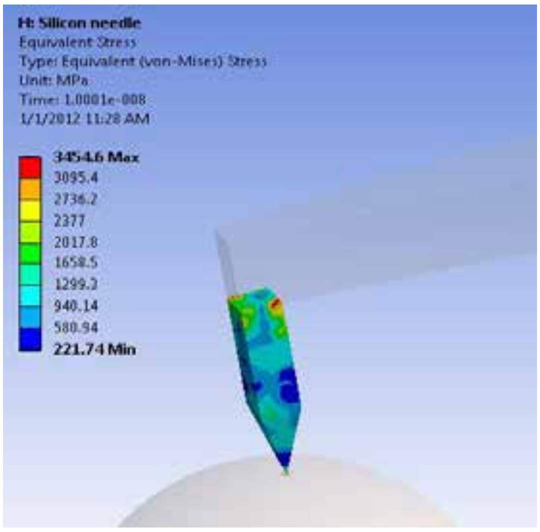

Fig. 13. Stress in needle at second time step when needle start puncturing outer layer.

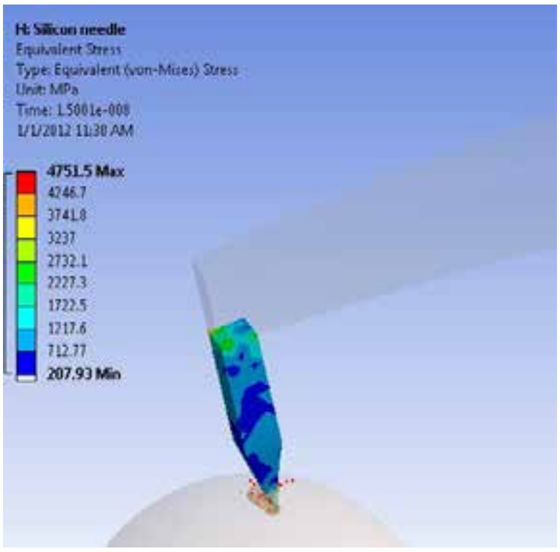

Fig. 14. Stress in needle at third time step when needle puncture the outer layer.

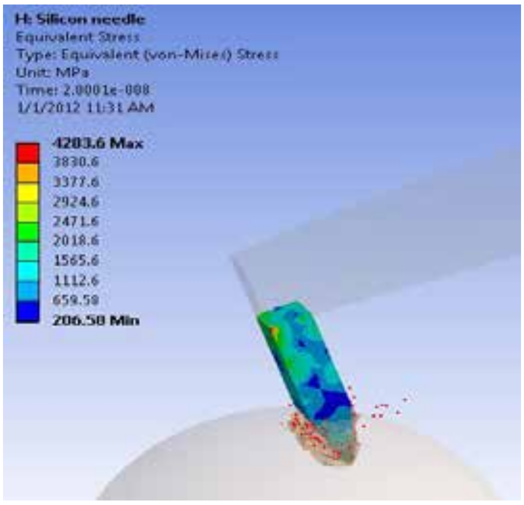

Fig. 15. Stress in needle at third time step when needle puncture the inner layer.

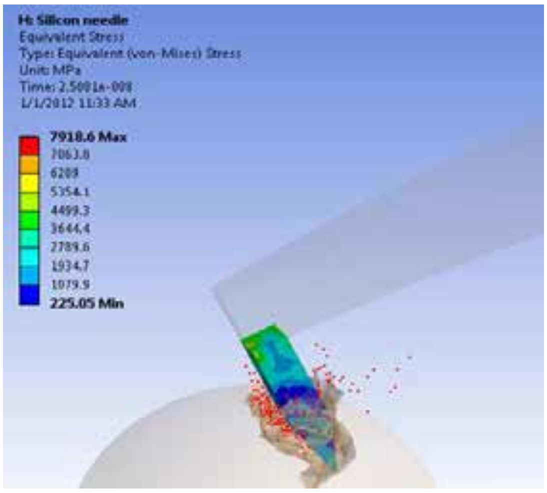

Fig. 16. Stress in needle at third time step when needle reached inside cell.

The stress distribution in complete device (cantilever beam with attached solid nanoneedle) is shown in Fig. 17, Fig. 18, Fig. 19, Fig. 20 and Fig. 21. Simulation results show that there is present a linear relation between applied load and stress. Similarly, the applied load is directly proportional to the bending of solid nanoneedle and cantilever.

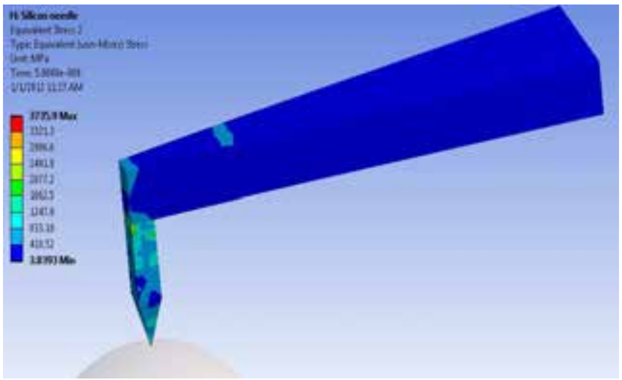

Fig. 17. Stress in needle and beam when needle touch the cell.

ISSN – 1999-4974

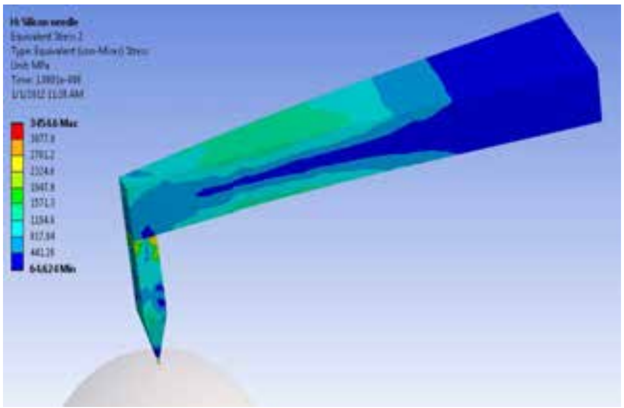

Fig. 18. Stress in needle and beam when needle start puncturing cell.

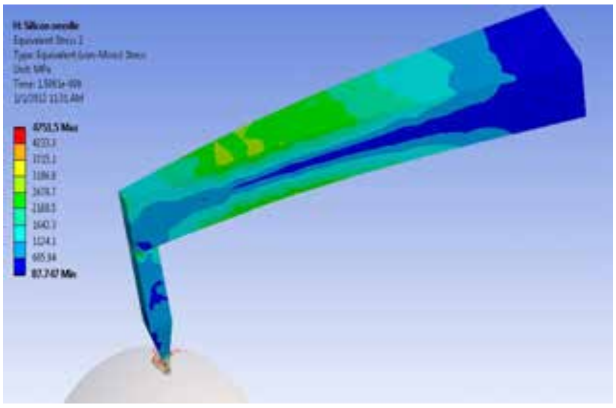

Fig. 19. Stress in needle and beam when needle puncture outer layer.

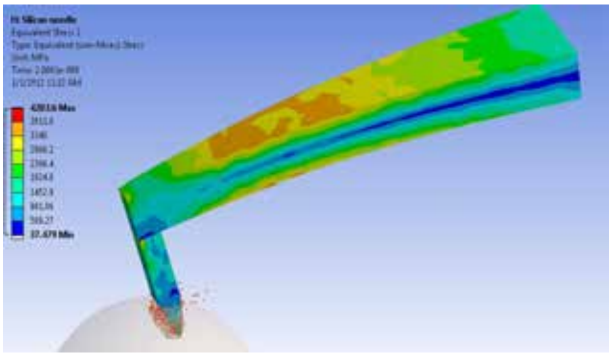

Fig. 20. Stress in needle and beam when needle puncture inner layer.

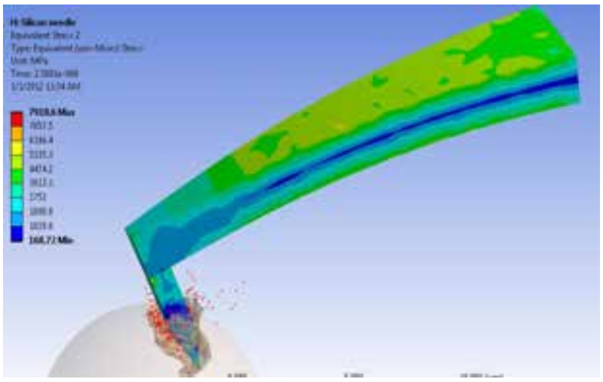

Fig. 21. Stress in needle and beam when needle reached inside cell.

IV. RESULTS AND DISCUSSIONS

The relation between deflection and stress in Si based solid nanoneedle at applied axial load from 10-100 mN is shown in Fig. 22. It has been observed that the deflection and stress increase linearly with the applied axial force.

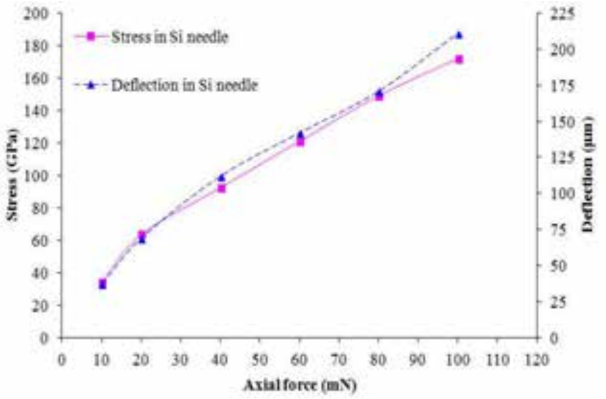

Fig. 22. Axial analysis of nano needle.

It has been observed that at applied axial load of 10 mN, the stress of 34.2 GPa and deflection of 37.2 μm have been achieved. The maximum stress of 172 GPa and deflection of 211 μm have been observed at applied axial force of 100 mN. As the force will increase from 100, the stress will increase from yield strength of the material. The relation between deflection and stress of nanoneedle at applied transverse force is shown in Fig. 23.

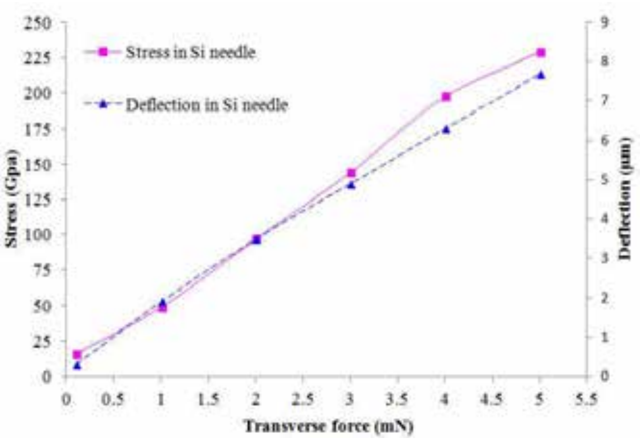

Fig. 23. Transverse analysis of nano needle.

The transverse force has been applied from 0.1 to 5 mN. At applied transverse force of 0.1 mN, the stress of 16 GPa and deflection of 0.3 μm have been achieved in nanoneedle. At applied transverse load of 5 mN, the stress of 229 GPa and deflection of 7.7 μm have been observed in solid silicon based nanoneedle.

By applying axial load from 10 mN to 100 mN, the stress and deflection has been observed in beam when needle is connected. At 10 mN axial load, the stress of 88 GPa and deflection of 38.2 µm have been achieved in the SIN beam. The maximum stress of 411 GPa and deflection of 227 µm have been observed at applied axial force of 100 mN in SIN beam as shown in Fig. 24.

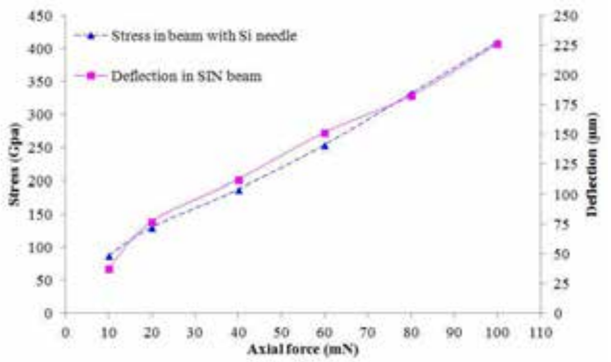

Fig. 24. Axial analysis of nano needle with beam.

By applying transverse load from 0.1 mN to 5 mN, the stress and deflection has been observed in beam when needle is connected. At 0.1 mN transverse load, the stress of 11 GPa and deflection of 0.5 µm have been achieved in the SIN beam. The maximum stress of 229 GPa and deflection of 4.1 µm have been observed at applied transverse force of 5 mN in SIN beam as shown in Fig. 25.

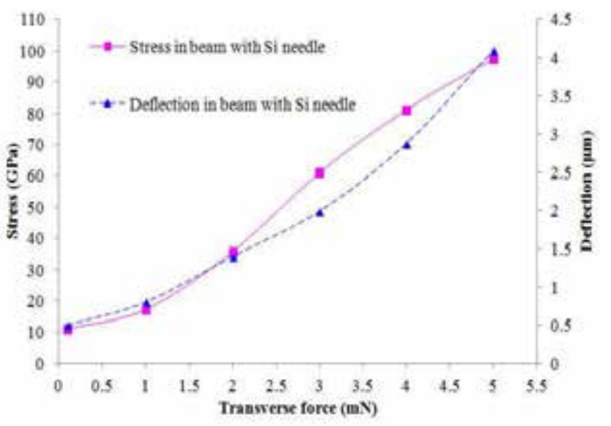

Fig. 25. Transverse analysis of nano needle with beam.

The above simulation results shows that presented device is useful for single cell surgery and multiple cells or tissue manipulation. The device can be used to puncture upper layer of single cell or penetrate the deeper part of cell or tissue. It can reach horizontally as well as vertically to different parts of the cell for manipulation. The presented device can be used for cell treatment, cell removal and drug delivery.

V. CONCLUSION

This paper presents the design and dynamic simulation of solid nano needle with square base attached with flexible AFM cantilever. This device is useful for cell surgery and tissue handling. Silicon and silicon nitride materials are considered for solid nano needle and cantilever. Hypo elastic single spherical cell was modelled and punctured during dynamic simulation. The length of needle is 104 nm and tip diameter is 250 nm. Axial and transverse load (force) from 10 mN to 100 mN and 0.1 mN to 5 mN respectively have been applied on the needle to foresee the bending and stress distribution in ANSYS workbench module. Low forces are required for cell manipulation. Therefore, the presented design of solid nano needle is suitable to bear low forces for single cell surgery. This device can also bear high forces for those applications that need higher forces.

REFERENCES

[1] S. E. Lyshevski, “MEMS and NEMS: Systems, Devices, and Structures”, CRC Press, 30-Oct-2013 - Technology & Engineering - 461 pages.

[2] S. Hardt, F. And Schonfeild, Microfluidic: *Fundamentals and Engineering Concepts in Microfluidic Technologies for Maniaturized Analysis System*, 1st Ed.; Springer, 2010.

[3] K. S. Birdi, “Scanning Probe Microscopes Application in Science and Technology”, CRC press, 2003.

[4] M. W. Ashraf, S. Tayyaba, N. Afzulpurkar, “Micro Electromechanical Systems (MEMS) Based Microfluidic Devices for Biomedical Applications”, *International Journal of Molecular Sciences*, 12(6):3648-3704, 2011.

[5] M. H. Rahman and M. R. Ahmad, “Finite element analysis of single cell surgery using rigid nanoneedle”, Biomedical Engineering and Sciences (IECBES), 2012 IEEE EMBS Conference, pp. 167-170, 2012.

[6] L. Xiaozhu, and Y Wang, “Structure and photoluminescence properties of Ag-coated ZnO nano-needles”, *Journal of Alloys and Compounds,* 509, pp. 5765-5768, 2011.

[7] I. Obataya, C. Nakamura, S. W. Han, N. Nakamura, J. Miyakea, “Mechanical sensing of the penetration of various nanoneedles into a living cell using atomic force microscopy”, Biosensors and Bioelectronics, Volume 20, Issue 8,c, pp. 1652–1655, 2005.

[8] M. R. Ahmad, M. Nakajima, S. Kojima,” In Situ Single Cell Mechanics Characterization of Yeast Cells Using Nanoneedles Inside Environmental SEM”, IEEE Transaction on Nanotechnology, Vol. 7, NO. 5, pp. 607-616, 2008.

[9] S. W. Han, S. Ryu, T. Kitagawa, H. Uetsuka, N. Fujimori, Y. Aoki, R. Ota, Y. Amemiya, N. Shimamoto, C. Nakamura, J. Miyake, “Evaluation of the insertion efficiencies of tapered silicon nanoneedles and invasiveness of diamond nanoneedles in manipulations of living single cells”, *Arch Histol Cytol.* 72 (4-5), pp. 261-70, 2009.

[10] C. E. Secu, M. Sima, “Photoluminescence and thermoluminescence of ZnO nano-needle arrays and films”, *Optical Materials*, 31, pp. 876–880, 2009.

[11] O. Chaudhuri, S. H. Parekh, WA. Lam, DA. Fletcher, “Combined atomic force microscopy and side-view optical imaging for mechanical studies of cells”, *Nat Methods.*, 6(5), pp. 383-7, 2009.

[12] T. Misu, K. Koh and T. Arai (2012). Fabrication of nano-needle arrays on diamond surface by reactive ion etching. MRS Proceedings, 1395, mrsf11-1395-n12-46 doi:10.1557/opl.2012.446.

[13] K. Yum, N. Wanga and M. F. Yu, “Nanoneedle: A multifunctional tool for biological studies in living cells”, Nanoscale, 2010,2, 363-372, DOI: 10.1039/B9NR00231F .

[14] J. D. Beard, R. H. Guy and S. N. Gordeev, “Mechanical Tomography of Human Corneocytes with a Nanoneedle”, Journal of Investigative Dermatology (2013) 133, 1565–1571; doi:10.1038/jid.2012.465.

[15] M. Hussain, Z. H. Ibupoto, M. A. Abbasi, X. Liu, O. Nur and M. Willander “Synthesis of Three Dimensional Nickel Cobalt Oxide Nanoneedles on Nickel Foam, Their Characterization and Glucose Sensing Application”, 2014. 14(3):5415-5425.

[16] A. Wong, X. Wang and J. Liu “Nano-needle structured, ambipolar high electrical conductivity SnOx (x ≤ 1) thin films for infrared optoelectronics”, J. Appl. Phys. 117, 103109 (2015); http://dx.doi.org/10.1063/1.4914910.