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Ming-fung Wong

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Adhesion of an Axisymmetric Film onto a Rigid Substrate: Application to a MEM-RF-switch

Ming-fung Wong
Mechanical Engineering, UMR

Abstract

A solid mechanics model is constructed to discuss the mechanical aspect of a MEM-RF-switch. A thin circular membrane clamped at the perimeter is adhered to a rigid cylindrical flat punch. A tensile load applied to the punch causes an interfacial delamination. Once the contact circle shrinks to 0.1758 – 0.3651 of the punch dimension depending on the magnitude of the tensile residual stress on the film, a spontaneous delamination, or "pull-off", occurs and the film snaps from the substrate at a critical load and punch displacement. The theoretical model has significant implications in MEMS that involves active moveable films.

1. Introduction

MEMS (MicroElectroMechanical Systems) is a rapidly growing technology in microelectronics. It is a miniaturized version of the macroscopic machines, e.g. gyroscopes, liquid pumps, sensors, etc. One interesting application is in wireless communication devices [1] such as mobile phone, radar, and signal filters. In this paper, a specific radio frequency (RF) capacitive switch is investigated. The device comprises a beam, 'bridge', which is electrically grounded and mechanically suspended above an underlying dielectric film, 'pad', coated on a signal line as shown in figure 1. When the microswitch is in "off" state and the bridge in "up-state", the bridge-pad gap is at its maximum, the capacitance is minimal and the RF signal flows in the signal line. When the switch is activated by an

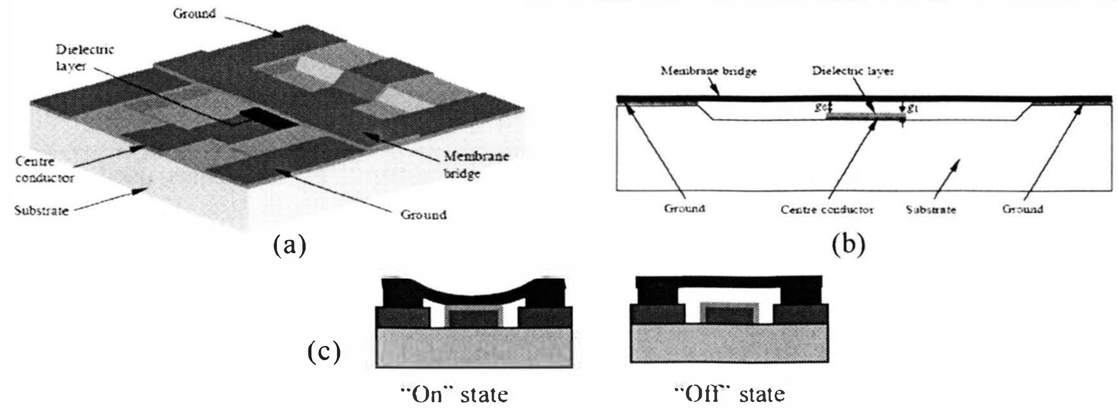

Figure 1. (a) 3-D model of a RF capacitive switch. (b) Cross section of a RF capacitive switch. (c) "On" and "off" states of the switch.

electrostatic attraction to "on", the bridge is pulled into contact with the underlying pad, resulting in a higher capacitance and signal switching occurs. Once the electrostatic force is turned off, the bridge is released and returns to its up-state. However, adhesion forces at the contact interface between the bridge and the dielectric film, coupled with intrinsic residual stress in the bridge, may hinder the capability of the bridge to break the contact, thus causing stiction failure. In theory, pad/punch interfacial adhesion energy and tensile residual stress on the bridge can affect the behavior of the performance of the capacitive switch, though studies in coupling of adhesion and residual stress are rare. Note that intrinsic residual stress arises from fabrication process, mismatch in coefficient of thermal expansion (CTE), and temperature rise during the switch operation.

Wan and Kogut [4] derived an elastic model for a flexible membrane with zero flexural rigidity such that only membrane-stretching is dominant. In this paper, the assumption is removed and the film is allowed to undergo plate-bending. A tensile residual stress is also incorporated into the new model. The coupling effect of interfacial adhesion and residual stress will be investigated.

	Actual Parameters	**Normalized Parameters**
Geometrical	$w(r)$ = deformation profile h = film thickness a = film / punch radius c = contact radius	$\xi = \frac{r}{a}$, $\zeta = \frac{c}{a}$, $\omega = \frac{w}{h}$ $\theta = \frac{\partial\omega}{\partial\xi} = \frac{a}{h}\frac{\partial w}{\partial r}$, $\theta' = \frac{\partial\theta}{\partial\xi}$,
Material	E = elastic modulus ν = Poisson's ratio κ = flexural rigidity = $\frac{E h^3}{12(1-\nu^2)}$ γ = interfacial adhesion energy (J.m^{-2}) σ_0 = tensile residual stress (N.m^{-2})	$\beta = a(\frac{\sigma_o h}{\kappa})^{½}$ $\Gamma = \left(\frac{a^4}{2\kappa h^2}\right)\gamma$
Mechanical loading	F = applied external force w_0 = vertical displacement of punch	$\varphi = \frac{Fa^2}{2\pi\kappa h}$

Table 1. A list of variables and their corresponding normalized quantities used in this paper.

2. Theory

Figure 2(a) shows the cross-section of a clamped circular film and the external loading by a cylindrical flat punch. Upon an external load, the diaphragm deforms by plate-bending and membrane-stretching deformations. The constitutive relation (or mechanical response) $F(w_0)$ *without* delamination will first be derived before proceeding to the delamination mechanism.

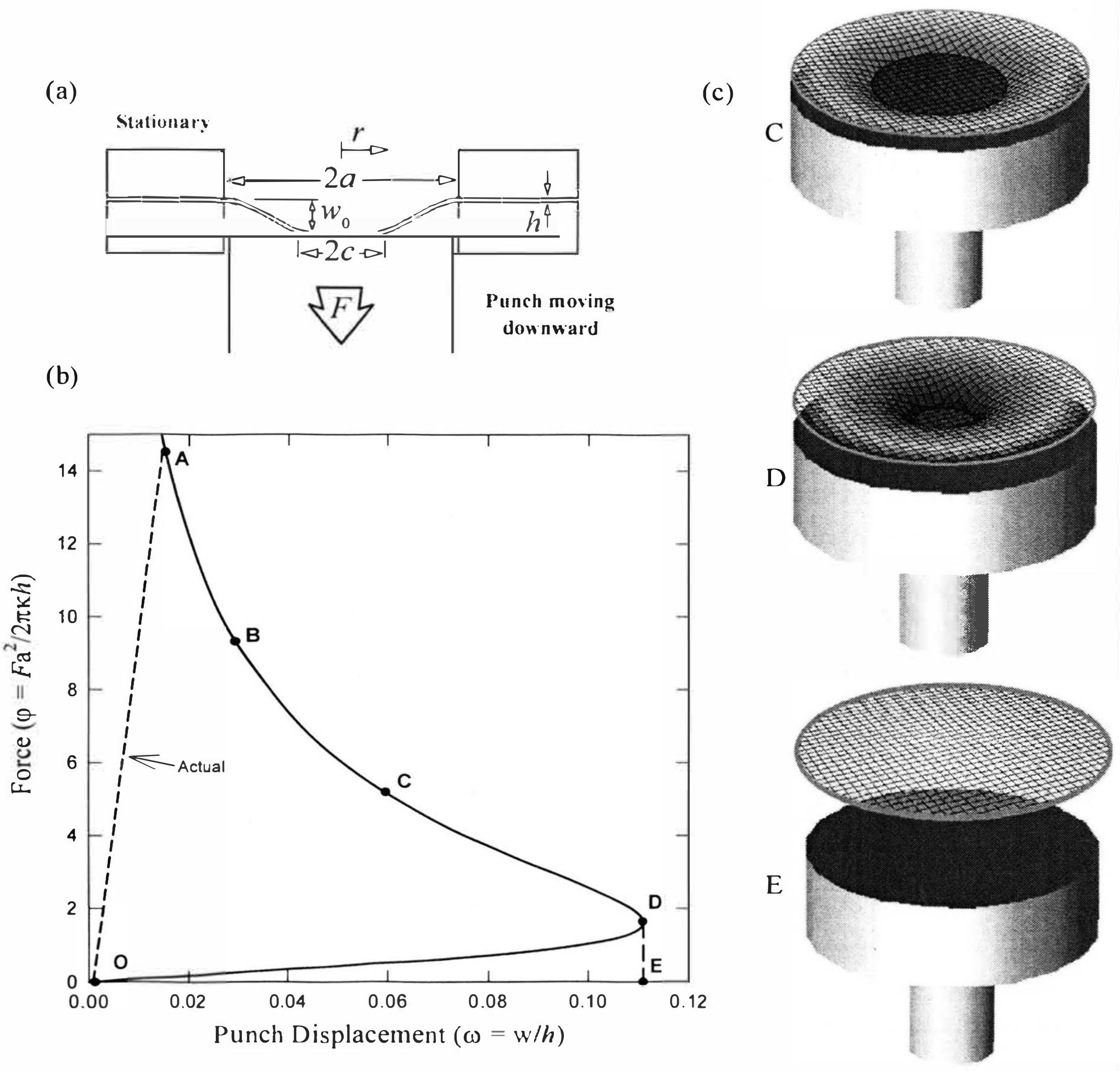

Figure 2. (a) The rigid film attached to the punch with interfacial adhesive energy. A tensile load is applied to the punch resulting in deformation and delamination of the film. (b) Constitutive relation for delamination. At O, the film is in full adhesion contact with the punch. Delamination begins at A, continues to B, then C, before "pull-off" occurs at D. The external load then drops to zero at E. (c) 3-D sketch of the delamination process.

2.1 Constitutive relation without delamination

For a film with non-zero κ and a tensile membrane stress σ_0, the deformed profile is governed by the von Karman equation.

$$\underbrace{\kappa \nabla^4 w}_{\text{plate-bending}} - \underbrace{\sigma_0 h \nabla^2 w}_{\text{membrane-stretching}} = \underbrace{F\,\delta(r)}_{\text{central external load}} \qquad (1)$$

where $\nabla^2 = \frac{1}{r}\frac{\partial}{\partial r}(r\frac{\partial}{\partial r})$ is the Laplacian operator in the polar coordinates, and the Dirac delta function, $\delta(r)$, denotes the central external load. The RHS of (1) is the mechanical input and the LHS the deformation. The profile gradient, $\theta = (a/h)(dw/dr)$, can be directly derived from (1), yielding

$$\xi^2\frac{\partial^2\theta}{\partial\xi^2} + \xi\frac{\partial\theta}{\partial\xi} - (1+\beta^2\xi^2)\theta = \xi\varphi \tag{2}$$

with boundary conditions, $\theta(1) = \theta(\zeta) = 0$ since the gradient at the clamped perimeter and the contact edge must vanish. Equation (2) is the modified Bessel equation [8] which gives

$$\theta = \varphi\left[C_1\, I_1(\beta\xi) + C_2\, K_1(\beta\xi) - \frac{1}{\beta^2\xi}\right] \tag{3}$$

where I_n and K_n are the n^{th} modified Bessel functions of the first and second kind, and C_1 and C_2 are constants to be fit to the boundary conditions:

$$C_1 = \frac{\zeta K_1(\beta\zeta) - K_1(\beta)}{\beta^2\zeta(-I_1(\beta\zeta)K_1(\beta) + I_1(\beta)K_1(\beta\zeta))} \quad \text{and} \quad C_2 = \frac{I_1(\beta) - \zeta I_1(\beta\zeta)}{\beta^2\zeta(I_1(\beta)K_1(\beta\zeta) - I_1(\beta\zeta)K_1(\beta)}$$

The profile is found by integrating θ with respect to ξ to give

$$\omega = \frac{\varphi}{\beta}\left\{C_1\left[-1 + I_0(\beta\xi)\right] - C_2K_0(\beta\xi) + C_3 - \frac{\log\xi}{\beta}\right\} \tag{4}$$

with the integration constant $C_3 = \frac{I_1(\beta)\mathrm{K}_0(\beta) - \zeta I_1(\beta\zeta)K_0(\beta) + \left[I_0(\beta) - 1\right]\left[K_1(\beta) - \zeta K_1(\beta\zeta)\right]}{\beta^2\zeta\left[I_1(\beta)K_1(\beta\zeta) - I_1(\beta\zeta)K_1(\beta)\right]}$.

The central displacement of the diaphragm, or equivalently, the vertical displacement of the punch is given by $\omega_0 = \omega(\zeta)$. The *linear* constitutive relation, $F(w_0)$ or $\varphi(\omega_0)$, can thus be found such that $\varphi \propto \omega_0$ as is obvious in (4). The presence of a residual stress stiffens the film such that the apparent elastic modulus increases.

2.2. Constitutive relation with delamination

The delamination mechanics is derived for a finite punch-film interfacial adhesion as follows. Once the tensile load exceeds a certain threshold, delamination begins. An energy balance method is adopted here. For an incremental decrease in contact radius, the total energy of the punch-film system is given by

$$dU_T = dU_P + dU_E + dU_S \tag{5}$$

where $U_P = Fw_0$ is potential energy, $U_E = \int F.dw_0$ elastic energy stored in the film, and $U_S =$ $= \gamma\,(\pi c^2)$ is the surface energy with γ the adhesion energy at the punch-film interface (J.m^{-2}). It can be shown that (5) requires

$$\gamma = -\frac{F}{2}\left[\frac{dw_0}{d(\pi c^2)}\right]_{F=\text{constant}} \quad \text{or} \quad \Gamma = -\frac{\varphi}{2}\left[\frac{d\omega_0}{d(\zeta^2)}\right]_{\varphi=\text{constant}} \tag{6}$$

Substituting (4) into (6) leads to

$$\varphi = \sqrt{\frac{f_1(f_2 + f_3 - f_4)}{8\beta^3\zeta^3\left[I_1(\beta\zeta)K_1(\beta) - I_1(\beta)K_1(\beta\zeta)\right]}\,\Gamma} \tag{7}$$

where $f_1 = -I_1(\beta)\left[K_0(\beta) - K_0(\beta\zeta)\right] - \left[I_0(\beta) - I_0(\beta\zeta))K_1(\beta)\right]$

$$f_2 = \beta\zeta\left[I_0(\beta\zeta) + I_2(\beta\zeta))(K_1(\beta) - \zeta K_1(\beta\zeta)\right]$$

$$f_3 = I_1(\beta)\left[\beta\zeta\, K_0(\beta\zeta) - 2K_1(\beta\zeta) + \beta\zeta\, K_2(\beta\zeta)\right]$$

$$f_4 = I_1(\beta\zeta)\left[\beta\zeta^2 K_0(\beta\zeta) - 2K_1(\beta) + \beta\zeta^2 K_2(\beta\zeta)\right]$$

The delamination process is illustrated in Figure 2b and 2c for a fixed adhesion energy $\Gamma = 1$ and zero residual stress $\sigma_0 = 0$. Delamination follows the trajectory OABCDE. When a load is first applied to the punch, delamination begins at A. A decreasing load is needed for the delamination to proceed along BCD. At D, $(d\varphi\ /\ d\omega_0) = (dF\ /\ dw_0) = \infty$, the delamination becomes unstable, the contact circle shrinks spontaneously to zero and the film snaps from the punch. This is known as the "pull-off" event in literature. The critical values of φ^*, ω_0^*, and ζ^* at "pull-off" can be measured experimentally, yielding the adhesion energy and residual stress. Note that the branch DO is a direct result from the mathematical energy balance, but is not physically accessible.

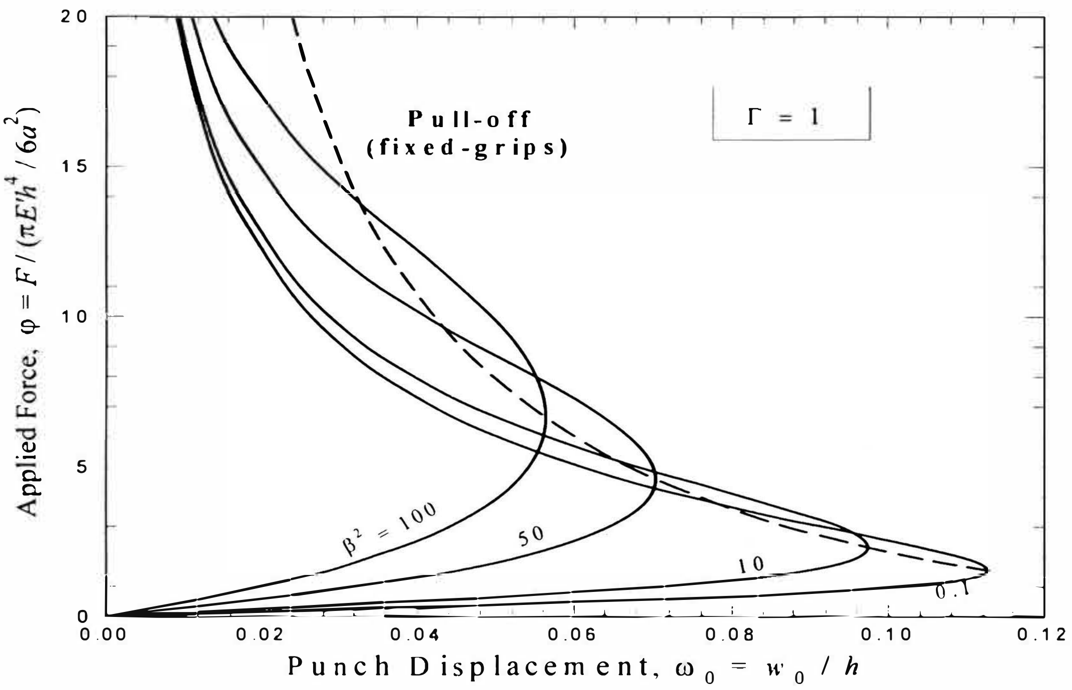

Figure 3. Delamination process is controlled by the coupling of adhesion energy and residual stress. At a fixed adhesion energy ($\Gamma = 1$), the residual stress shifts the "pull-off" event to a larger applied force and a smaller punch displacement.

Figure 3 shows the effect due to residual stress (β_0 or σ_0) at a fixed adhesion energy. The "pull-off" event occurs at a larger external load (φ^* or F^*) and smaller punch displacement (ω_0^* or w_0^*) as a result of the residual stress stiffened membrane. Figure 4 shows the corresponding changes in contact radius (ζ^* or c^*) as a function of residual stress. At small σ_0, the adhesion energy is the dominating factor in the delamination mechanics and ζ^* approaches 0.1785. This contact dimension increases as σ_0 augments. At large σ_0, the residual stress prevails and ζ^* approaches 0.3651.

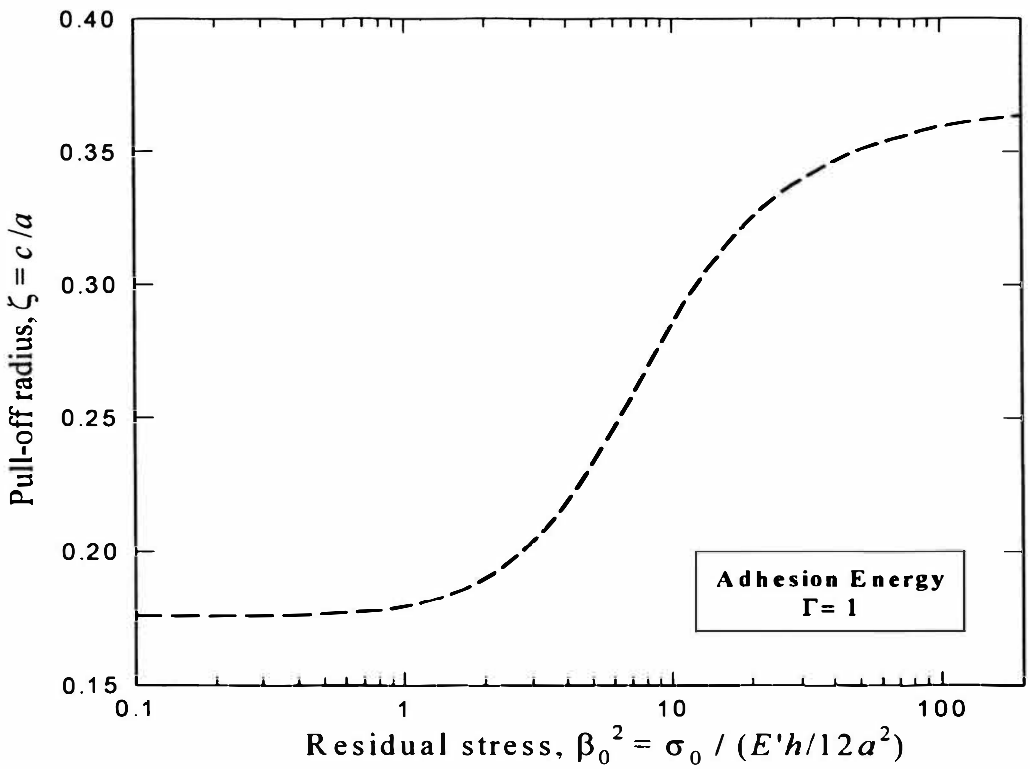

Figure 4. The pull-off radius increases as tensile residual stress increases. At small residual stress ($\beta^2 < 2$), the pull-off radius approaches 0.1758. After a transition around $\beta^2 = 10$, the pull-off radius approaches 0.3651.

Discussion

In designing a RF MEMS, according to figure 4; if a high bounce-back required, a highly preloaded film has to be made very close to the bottom plate; if a reasonable distance between the film and bottom plate, the film can be less preloaded, but the short side would be smaller contact area between the film and the bottom plate and there might be some bad effect on the circuit performance.

High residual stress does not have to be a good design as well, in figure 3, it shows that high residual stress film require a bigger force to pull it toward the punch. In reality, high residual stress result in high current flow in pad for higher electrostatics energy and a series of operation and mechanical issues. For example, higher current result in higher heat generation which lead to heat transfer concern; bridge fatigue with high residual and short operation lift is resulted. However, all these reality issues have not be a concern in this research paper, further study will be done alone these lines.

Conclusion

A mathematical model is constructed to show the delamination mechanics of a stiff circular membrane adhered to a rigid punch. The constitutive relations are derived for situations with and without delamination using an energy balance method. The residual stress in the membrane has a significant effect on the mechanical behavior of the punch-film system. The trends and graphs given here will have significant impacts on the design and fabrication of many MEMS devices, especially those involve moveable circular or rectangular membranes.

References

[1] J.-M. Huang, A.Q. Liu, C. Lu, J. Ahn, Mechanical characterization of micromachined capacitive switches: design consideration and experimental, Sensors and Actuators A 108 (2003) 36-48.

[2]P.M. Osterberg, S.D. Senturia, M-test: a test chip for MEMs material property measurement using electrostatically actuated test structures, J. Microelectromech. Syst. 6 (2) (1997) 107-108

[3]P. Osterberg, H. Yie, X. Cai, J. White, S. Senturia, Self-consistent simulation and modeling of electrostatically deformed diamphragms, in: Proceedings of the Micro Electro Mechanical Systems Workshop, MEMs'94, Oiso, Japan, 1994, pp.28-32

[4]K.T. Wan, L. Kogut, The Influence of Residual Stress on Micromachine Stiction: ASME/STLE International Joint Tribology Conference. (2004) TRIB 2004-64333.

[5]Abramowitz, M. and Stegun, I.A., *Handbook of Mathematical Functions*(National Bureau of Standards, John Wiley, New York, 1959).

Opportunity of Undergraduate Research Experience to me

The project I worked on for this undergraduate research program is about thin film mechanics. In this research, I learned the relationship between the tensile residual stress to the performance of the film. The idea of this research came from the similar situation in MEMs device. However, my professor Dr. Wan from Mechanical Engineering Department gave me a brain shock on how a single knowledge being applied into so many different kinds of study. Thin film mechanics behavior is not only the major issue of the performance of MEMs devises, it also affects the performance of our eyes, the behavior of normal cells and malfunction cells, and etc. Even today progression of this research is still far from entering any specifics field, the reference and information I read greatly furnished my knowledge.

The source of my information is mostly came from Dr. Wan previous papers and related papered from library journal resource. Some of the information came from meeting with different professors in other fields. For me, reading is boring but not understanding, so I compared different papers and my research, then found out why that information related to my research. This why I understood the information a lot better and information research became a fun part of the research. On the other hand, talking to other professors was fun too. They were always doing something that I never heard of and somehow related to my research. One of them was Dr. Ravi in Washington University in St. Louis. He was an eye doctor. I learned the membrane rigidity of the lens related to the performance of the eyes. In conclusion, I think absorbing knowledge is not the best way to learn. Instead, understanding the relationship of the knowledge to my work is the best use of knowledge.

The experience from this research is not just about the book, it also improved my technical writing skill and learning skill. Technical writing would help me better express my idea to other people and better skill of learning gives a new way to understand the world of knowledge. I think I gained life time benefit from this research experience.