Comparative Investigation Using GaAs(950nm), GaAIAs (940nm) and InGaAsP (1450nm) Sensors for Development of Non-Invasive Optical Blood Glucose Measurement System

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***Abstract*—Previously, many researches had been done on non-invasive using near-infrared sensing. Sia [1] had investigated near-infrared sensing using signal penetrating finger method. However, by using finger penetration, there are no results obtained. He only obtained signal using glucose concentration. Therefore the objectives of this research are to investigate the performance of three different wavelength of sensors; infrared 940nm and 950nm and also near-infrared 1450nm. Sensor that gave the best output had been chosen to design a non-invasive optical blood glucose measurement device. Generally, the overall system consists of three parts including sensor part, signal conditioning circuit, and also numerical display. The initial design tested by considering initial voltage 1.616V to 1.68V which referred to previous research by Sia [1] as the output of the sensor. Then proceed by using test tube which contains various percentage of glucose concentration. The same methods had been used to the human samples fingers instead of test tube. From the experiment, output graph of the 950nm shows more consistent pattern compared to the 940nm. 950nm also has a larger range scale for voltage which from 5.016V to 5.4633V compare to the 940nm voltage range scale which from 5.0327V to 5.4201V. Further test on human finger had been done by using 950nm infrared but the output voltages were too small. The performance of the measurement can be improved by controlling the surrounding condition and fixed the path length between transmitter and receiver. Test using test tube showed that the near infrared and infrared were capable to predict different glucose concentration. By using circuit designed, it can be seen that the voltage reading became higher compared to before meal. Therefore, it can be concluded that the circuit design functions accordingly and also the non-invasive. During human sample test, increment pattern can be seen from fasting to non-fasting condition but the main effect is all samples have different fingers' diameter which each of user needs to be calibrated.**

***Index Terms*—Infrared, Near-infrared, Non-invasive, Blood Glucose.**

I. Introduction

Based on the data by International Diabetics Federation (IDF) [2] in year 2010, there were 284.6 millions of diabetes patients globally. IDF estimated that the total of people around the world with diabetes, will doubled with increment of 54% in year 2030. The number is very large and people should be aware of this matter. **Figure 1.1** below has shown the global projections for number of people with diabetes in year 2010 and 2030 in whole wide world. Moreover, having diabetes also can lead one to blindness, kidney failure, heart attack, stroke and amputation. Yearly, there are four million people died because of diabetes.

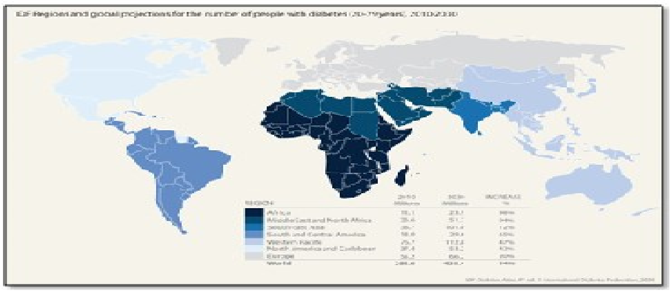

Figure 1.1 IDF Regions and Global Projections for Number of People with Diabetes (20-79 years), 2010-2030 (Picture courtesy of IDF Diabetes Atlas [2]

To date, people in the entire world mostly live in unhealthy daily routines and lifestyles which can lead to illnesses. Based on research by M. Mafauzy, Z. Hussein and S. P. Chan [3], quality of life evaluation showed that about one third of diabetis patients in Malaysia have poor quality of life. For example, dietary is one of the caused that can increase people's blood glucose reading which also known as diabetes. Dietary including eating time, type and amount of the food especially carbohydrates which give large effect to the blood glucose level. However, glucose is also important since it is the main carrier of energy in the human organism [4-6]. The most important factor is that the amount of food that we take should be suitable with our daily activities. Besides, lack of exercise and physical activities plus stress can also increase the level of glucose. It is better if people can check their blood glucose level once in a while because knowing their health condition can make people appreciate more with their lives. People also can make adjustment to improve their lifestyle and control meals they eat. For diabetes patients, it is important for them to regularly test and record the result to see the improvement of their health by changing their lifestyle. Hence, the existence of the portable blood glucose self check device is very helpful to the patients.

II. METHODOLOGY

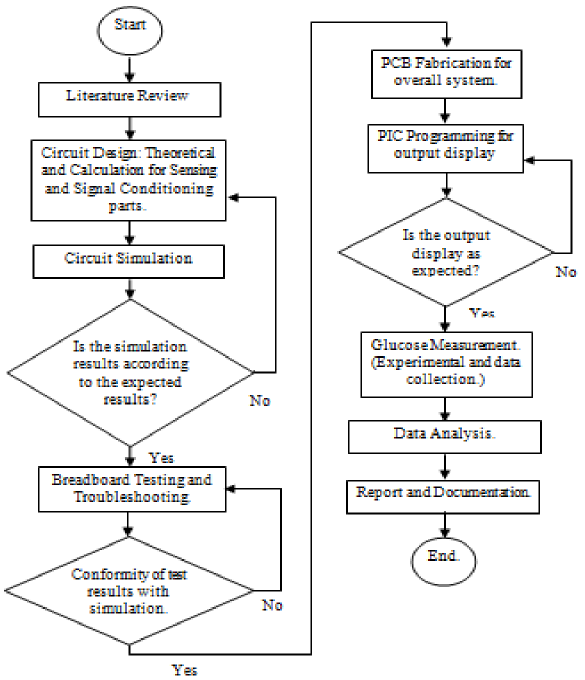

Figure 2.1 Flow chart of the overall process in construct this project.

Figure 2.1 shows the flow chart of the overall process required in this project. Starting by doing detail research and literature review related to this topic. From the literature review, the findings of each research had been analyzed which lead to research problems. Besides that, advantages and disadvantages of the method used in each research had been identified. With the research and literature that had been done, the focus in the topic can be smaller and more specific and objectives of the project then were created.

As the next step, circuit had been designed. Designing started by theoretical calculation. Generally, the system need three parts which are sensing part, signal conditioning circuit and Programmable Integrated Circuit (PIC) as the display. Theoretically, the circuit had been designed and voltage output for each step had been calculated and considered. From that, all the components required can be listed.After that, the simulation for the preliminary designed circuit had been done. The output voltage for each stage of signal conditioning circuit had been tested to make sure that the results are according to the expected results as in the calculation.With the circuit design, process had been preceded with the assembly on the breadboard. Troubleshoot had been done to make sure that the output results were similar to the results in the simulation. Then the data from the simulation had been collected. PCB for overall of the system had been designed and fabricated. The system had been tested in two main tests which are by varying concentration of glucose solution and also with the human finger as samples. To verify and support the output result, the human samples also had been tested with commercial finger-prick method. The output results had been compared as the verification. Programming for the PIC had been developed as the numerical output display of the system. The program had been done to make sure that the output can display the status of the output reading if either with low, medium and high blood sugar. All the experiments had been done by testing with both by varying concentrations of glucose solution and also by testing on the real human finger as samples in the experiments. All data had been collected and then analysed. Lastly, by completing all the steps and all the data had been analysed, the report was written and documentation had been done.

III. RESULT AND DISCUSSION

TABLE I Result of experiment using test tube

Glucose Concentration (%)	Vo Photodiode (V) (1450nm)	Vo Photodiode (V) (940nm)
100	0.938	0.4831
90	0.937	0.4745
80	0.935	0.4668
70	0.934	0.4458
60	0.933	0.4499
50	0.933	0.4515
40	0.933	0.4477
30	0.933	0.4544
20	0.933	0.4541
10	0.932	0.4367

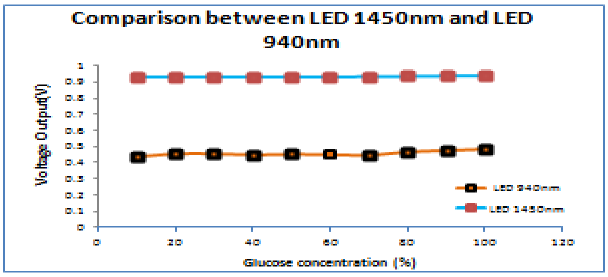

Figure 3.1 Comparison between LED 1450nm and LED 940nm output

Since the output readings of both transmitters are not affected by different percentage of glucose concentration, circuit design had been adjusted from the initial design. These show that the output voltage from the photodiode too small compared to the initial input voltage that had been considered while designing the circuit. The stage of amplification had been amplified higher to make sure that the voltage readings are much higher than the previous output. Linearization part had been adjusted as suitable to the output reading as long as the final output voltage are not exceed than 5V.

TABLE II Glucose Reading for 940nm and 950nm

%	Infrared Wavelength	
	940nm	**950nm**
100	5.4201	5.4633
90	5.3396	5.2812
80	5.2489	5.2225
70	5.2045	5.2138
60	5.276	5.2064
50	5.1891	5.182
40	5.1625	5.147
30	5.151	5.128
20	5.1345	5.087
10	5.0771	5.053
0	5.0327	5.016

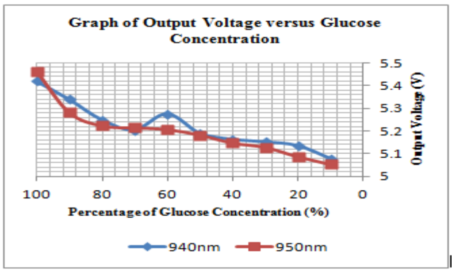

Figure 3.2 Graph Output Voltage of 940nm and 950nm versus Glucose Concentration.

Figure 3.2 shows, the different voltage output reading from two IR wavelengths which 940nm and 950nm. From the graph, the 950nm looks more consistent compare to the 940nm. 950nm also has a larger range scale for voltage which from 5.016V to 5.4633V compare to the 940nm voltage range scale which from 5.0327V to 5.4201V. The percentage increase between 940nm and 950nm is 5.99%.Based on test of varying percentage of glucose concentration, it shows that the 950nm infrared give better and more stable output, further test on human finger had been done by using 950nm infrared as the transmitter of the device. The test had been done using human finger as the sample. The finger is placed between phototransistor and photodiode. The output reading is measured by using multimeter at the last stage of the signal conditioning circuit.

TABLE III Human Sample Reading

No.	Weight (kg)	Height (cm)	Fasting (V)	Non-Fasting (V)	Percentage Difference (%)
1	96	171	0.13096	0.1710	23.42
2	91	175	0.1340	0.1590	15.72
3	55	160	0.2014	0.3056	34.10
4	73	174	0.1004	0.1300	22.77
5	67.6	173	0.1027	0.1202	14.55
6	64.5	170	0.1820	0.1940	6.19
7	56	163	0.1460	0.2080	29.81
8	57	158	0.1335	0.1815	26.45
9	63	169	0.2360	0.2560	7.81

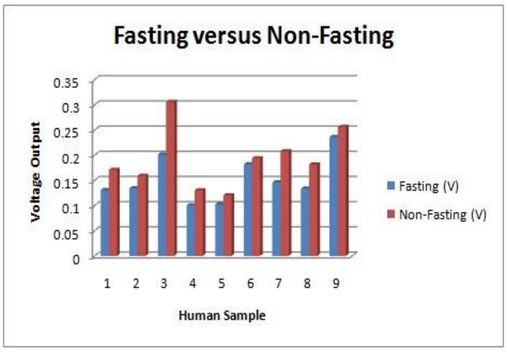

Figure 3.3 Fasting versus Non-Fasting

From TABLE III and **Figure 3.3** above shows that there are increments in voltage reading after having meal compared to during fasting. Even though the output voltage is small values, but then the pattern of increments still can be seen. The pattern of effect after taking meals also can be accepted since after having meals, the blood glucose reading for each volunteer are increasing.

A. COMPARISON ANALYSIS BETWEEN INFRARED AND NEAR INFRARED SENSOR TESTING

Light emitting diode, LED is a complex semiconductor coverts electrical signal into corresponding light signal. The advantages of using LED are small in size, high radiance which emit lots of light in a small area, high in reliability and can be modulated (turned on and off) at high speed [7].Based on the application that needs to be used, there are several LEDs' performance characteristics that can be determined such as peak wavelength, spectral width, emission pattern, power and speed. The peak wavelength is the wavelength where the source emits most power. Spectral width is the range of wavelength that light is emitted in practise which also known as spectral width of the source [7]. There are two types of LED structures which are edge emitters and surface emitters. The differences of these two types are edge emitter LED is more complex and expensive. The emitting spot also small resulting high output power. While surface emitter LED have simple structure and comparatively inexpensive. It offers low to moderate output power levels and low to moderate operating speed [7].LED optical output is approximately proportional to drive current. Temperature is one of the factors that affect the optical output. **Figure 3.4** shows the detail of the typical behaviour of LED.

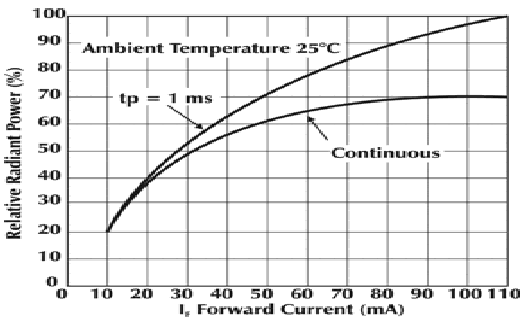

Figure 3.4 Optical Outputs vs. Current in LED (Picture courtesy from fiber-optics.info [53]).

LEDs have voltage drop about 1.1 to 1.5 Volts. Shorter wavelength diodes have largest voltage drops [7] of the LED. For all LEDs used in this work, voltage drop of LED 940nm is 1.35V, LED 950nm is 1.3V while LED1450nm is 1.2V. From that, the pattern can be seen where as the wavelength increases, the voltage drop decreases. This is due to the bandgap energy, E_g which higher wavelength have smaller energy gap and resulting smaller voltage drop.

$$E_g = hc/l = 1240\text{eV-nm}/l \qquad \ldots(1)$$

Where:
h = Plank's constant = 4.13×10^{-15} eV.s
c = speed of light = 2.998×10^{8} m/s
l = wavelength in nm

From equation above, the energy gap of LED based on its emission wavelength had been predicted as in TABLE IV.

TABLE IV Common Light Emitter Materials and Characteristics.

Material	Formula	Energy Gap	Wavelength
Gallium Phosphide	GaP	2.24 eV	550 nm
Aluminum Arsenide	AIAs	2.09 eV	590 nm
Gallium Arsenide	GaAs	1.42 eV	870 nm
Indium Phosphide	InP	1.33 Ev	930 nm
Aluminum-Gallium Arsenide	AIGaAs	1.42-1.61 Ev	770-870 nm
Indium-Gallium-Arsenide-Phosphide	InGaAsP	0.74-1.13 Ev	1100-1670nm

From TABLE IV, shows that there are variation of material used in LED. In this work, three variation of materials had been used which are GaAlAs (940nm), GaAs (950nm) and InGaAsP (1450nm). Voltage drop which also called as forward voltage is indicated the energy gap that corresponds to the energy of the emitted photons. LED current can be calculated from the known voltage drop and saturation voltage of the transistor. Equation below shows the general form of the calculation [7].

$$I_{LED} = V_{POWER} - V_{LED} - V_{SAT}/R_3 \qquad \ldots(2)$$

Where:
V_{POWER} = DC power supply voltage
V_{LED} = forward voltage drop of the LED
V_{SAT} = drive transistor saturation voltage
R_3 = series LED current limiting resistor
I_{LED} = peak LED current

Experiment and testing had been done in controlled environment since LED is sensitive to ambient light condition [7]. All experiments had been done in same laboratory with fixed position of devices in the experiment setup.

B. REFINEMENT OF NEAR- INFRARED TESTING

As the same signal conditioning circuit used with the near-infrared, the result of output voltage during human finger test shows no changes. The circuit was redesigned for the near-infrared testing. And did the re-test to test either the sensor can give better output or not. The linearization circuit had been removed from the design since output from low pass filter was not exceeding 5V.

1) Test Tube Experimental

Experiment had been done using the difference of glucose concentration and the output readings from the test are as below:

TABLE V Output Voltage of 1450nm Vary Glucose Concentration Test

Glucose Percentage (%)	Glucose Concentration (mg/dL)	Output Voltage (V)
100	200	3.4174
90	180	3.2009
80	160	2.9830
70	140	2.8120
60	120	2.4763
50	100	2.2880
40	80	2.1062
30	60	1.5711
20	40	1.1660
10	20	0.8730
0	0	0.6000

Figure 3.5 shows the output pattern of the output voltage from the test of different glucose concentrations. Graph shows that the voltage is nearly direct proportional to the percentage of glucose concentrations. From the pattern, it shows that when the percentage of glucose concentration is high, voltage output also high and vice versa.

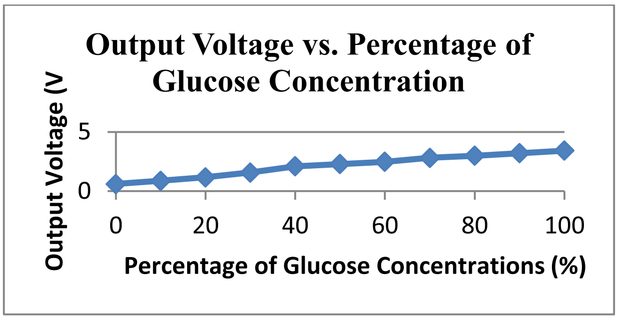

Figure 3.5 Graph of Output Voltage vs. Percentage of Glucose Concentration

Based on Diabetes Research and Wellness Foundation [8] shows that random blood sugar in normal reading is from 80 to 139mg/dL and one will consider have diabetes when the glucose reading is 200mg/dL and above. From the data that had been collected, by comparing output voltage with the glucose concentration, the results are successful in getting the relationship between the output voltage readings with the output display of PIC.

2) Human Sample Final Testing

As all the test and experiments had been done previously, the most suitable sensing part of the system is using LED1450E pairing with photodiode FGA01FC. In previous test also try and error of the signal condition circuit had been done in order to give the best and most accurate output results. After the finalized all the components and circuit construction, the actual testing had been done with 17 volunteer as the human sample. In this test, another factor also had been taken. The test consists of body mass index, blood pressure and also their heart beat. These elements had been observed to see if there are any effects to the output reading.Test also had been done using the present design. Reading had been taken twice to make sure the repeatability of the system. Lastly, volunteer also had to do the blood glucose test using commercial meter with the finger pricking method as verification. The commercial reading had been taken to test the performance of the present designed. Test of both blood glucose meters had been done in two different conditions which are during fasting and non-fasting. Volunteer had been asked to fast for at least eight hours. At 10 am, the first test had been done and the data obtained considered as during fasting. After that, they had their breakfast which the meals also had been controlled. All of them had been given same meals which each of them had one wrapped nasi lemak and 250ml of sugar added fruit juice. After two hours, second reading had been taken as the non-fasting condition.Results obtained had been taken and as in Table 25. From the data that had been collected, by comparing output voltage with the glucose concentration, the results are successful in getting the relationship between the output voltage reading to the output display of PIC where had been programmed.

TABLE VI Overall Results of Near-Infrared Human Testing.

Blood Glucose Reading					
Before Meal			After Meal		
Commercial Meter (mmol/L)	Present Designed (V)		Commercial Meter (mmol/L)	Present Designed (V)	
5.8	1.7111	1.7069	7.1	1.7283	1.7191
5.6	1.6412	1.6352	5.0	1.6571	1.6790
5.5	1.6407	1.6547	5.9	1.6510	1.6549
5.4	1.6521	1.6466	6.3	1.6760	1.6677
5.4	1.6659	1.6493	5.2	1.6615	1.6570
4.9	1.7056	1.6776	5.7	1.6509	1.6596
4.9	1.6622	1.6570	5.5	1.7238	1.6583
4.8	1.3762	1.6644	5.4	1.7123	1.6929
4.7	1.6712	1.6573	6.7	1.6436	1.6522
4.7	1.6754	1.6893	5.8	1.6828	1.6900
4.6	1.6827	1.6976	6.0	1.7107	1.6970
4.6	1.6596	1.6421	5.4	1.6496	1.3501
4.6	1.6696	1.6419	6.1	1.6973	1.3669
4.5	1.6620	1.6544	4.3	1.6634	1.3524
4.3	1.6843	1.6988	5.0	1.7025	1.3833
4.3	1.6888	1.6717	4.7	1.7345	1.7266
3.9	1.6848	1.6907	5.2	1.7239	1.7819

From TABLE VI, it can be seen that all the human samples taken are in normal range of blood glucose reading. This is due to the fact that the samples are taken from healthy students at the age of 23 years old with no diabetic condition. The testing is only to prove that the circuit designed functioning well with verification using commercial glucose meter. However, from the observation of the output readings, the output voltages are not consistent compared to the commercial meter. This may occurred because of the different finger diameter size of each person that effected the signal penetration through different person. But then, increment pattern still can be seen from fasting to non-fasting condition for every sample. The obvious effect is all samples have different fingers' diameter which each of user needs to be calibrated.

C. PIC OUTPUT DISPLAY

When the development of sensory part is complete, several experiment is conducted to determine whether the instrument that have been develop was able to process the electrical signal given by photodiode and display it on LCD. The experiment was implementing by using led with wavelength 1450nm as transmitter and InGaAs photodiode as receiver to measure glucose concentration. The suitable voltage range needed to interface with microcontroller is between 0V to 5V. Therefore the photodiode output voltage was linearized into the suitable range. By using the same configuration of linearization and summing amplifier that has been discussed in previous chapter, the photodiode output voltage are able to converted into a suitable range to operate with microcontroller. **Figure 3.6** show the result from display panel that display the result from the experiment after be processed by signal conditioning circuit.

Figure 3.6 Output Reading Display.

IV. Conclusion

The first objective had been achieved by comparing the performance of infrared and near-infrared as the sensing device of non-invasive blood glucose. The instrument based on self-monitoring glucose level was developed as and the experimental processes had been done well. Signal conditional circuit was able to filter noise produced by near infrared sensor by blocking high frequency. The benefit from noise filtering is better glucose signal can be measured and accurate reading can be obtain. Besides that, signal conditioning circuit was able to amplify the input voltage from near infrared sensor into suitable value to be observed. The output from signal conditioning circuit are also successful be linearize from 0V to 5V. From that voltage range, the signal conditioning circuit was able to interface with microcontroller. The input from signal conditioning circuit was able to be converted to digital value. By displaying the digital value on display panel, people will be able to determine their glucose level which leading them to better lifestyle.It can be concluded that the circuit design can functions accordingly and also non-invasive. During human sample test, increment pattern can be seen from fasting to non-fasting condition but the main effect is all samples have different fingers' diameter which each of user needs to be calibrated. The calibration also may due to different people have varying amounts of protein, fats and water. Besides, doing measurement on the skin tissues, the absorbance spectra can be affected by other elements contained in blood such as water, albumin, globulin and also environmental factors. However environmental lighting, temperature and humidification had been controlled by doing all the experimental process in the same room.

V. Recommendation For Future Work

From the observation of the output readings, the output voltages are not consistent compared to the commercial meter. It shows that there are errors occur in the system. This may occurred because of the different diameter size of each person that makes different penetration trough the different person. But then, increment pattern still can be seen from fasting to non-fasting condition for every sample. The obvious effect is all samples have different fingers' diameter which each of user needs to be calibrated. So it suggested in future work to add calibration knob or reset button so that for every testing with different patient as sample, the reading will starts at '0'.

Besides, the instrument based on self-monitoring glucose level still can be enhanced by adding trigged alarm. Different type of triggered alarm that produces different type of sound can be used to indicate which glucose level that has been measured. This method was recommended to overcome the problem to those have blurred vision especially older people. The current instrument need to be power up by using two direct current supplies with needed voltage 18V. As recommendation, the future instrument can be powered by using lithium battery so that the instrument can be carry out easily and can be use anytime and anywhere.

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