Design & Implementation of a Low Cost Blood Glucose Meter with High Accuracy

Shumit Saha, Nayan Sarker, Avijit Hira
Department of Electronics & Communication Engineering
Khulna University of Engineering & Technology, Khulna, Bangladesh
shumit.ece.kuet@gmail.com, nayan_ece09@yahoo.com, avi_ece910@yahoo.com

Abstract— **Diabetes Mellitus mostly known as "Diabetes" is a worldwide common and serious health issue. Across the world approximately 175 million people at present are with diabetes and this will increase to 366 million by the year 2030 according to World Health Organization statistics. People suffering from diabetes are solely dependent on exact blood glucose concentration information. Glucometer is a device which helps to detect blood sugar levels in human body. In developed countries people widely use this medical device. But in developing countries like Bangladesh the usages of this helpful devices is limited to a very few people; due to illiteracy, cost, publicity etc. In this paper, a real time blood glucose meter is designed & implemented which is very low in cost, targeting the poor people in developing and underdeveloped countries. This proposed meter uses transcendental concentration equation over the linear equation used in existing commercial meters. Due to this, the average deviation of result is much smaller than the commercial one. Result shows that the proposed meter gives around 93% accuracy with pathological data tested over 38 persons. Total cost of the proposed glucometer is only 5 USD so that poor people can have an easy access to this meter.**

Keywords— Diabetes; Glucometry; Insuline; RBS; EGBTS; Embedded System; Low-Cost; High-Accuracy.

I. Introduction

Blood Glucose Meter (BGM), much familiar as 'Glucometer', is a small, portable electronic device widely used to measure the level of glucose concentration in blood. Depending on the glucose concentration level, drug might be required for patient if necessary. A test strip is associated with glucometer to interact with glucose presence patient's blood drop.

There are several glucometers available in market. But, the price range of these glucometer varies from 1200 to 2500 BDT. But, there is no glucometer available in market which price is less than 1000 BDT. Moreover, the accuracy of the commercial glucometers varies between 85 and 90 percent. This because the commercial glucometer offers Liner equations to relate the glucose concentration and the voltage found from EBGTS. But, in practice, the relationship between the glucose concentration and the voltage is taken from EGBT progresses discretely. Hence, to accomplish the task of curve fitting, a significant deviation will be occurred to linearize the discrete function. This deviation results much inappropriate glucose level.

In this paper, a glucometer is designed and implemented with considering these two major drawbacks of commercial glucometer. The proposed meter is much more low cost than available meters in market and it gives higher accuracy than commercial one. The proposed blood glucose meter is built with the ATMEGA8A AVR microcontroller. The software part is done using the C programming in AVR studio. Hence, the cost remains low because this system use microcontroller. Besides, to consider the accuracy as the cardinal priority, the proposed design introduces transcendental approach to relate the relationship between the glucose concentration and the voltage from EGBT progresses which offer less deviation. Eventually, it is feasible to obtain much accurate result than traditional linear approach.

The theoretical background, design methodology, implementation technique of the system, result & performance and meter specification will be discussed briefly in the following sections. This blood glucose meter provides many features like low cost, high accuracy, higher sensitivity, lower error rate, portability.

II. Theoretical Background

A. Diabetes – from biological view

Normally, the body decomposes starch and transforms it to glucose as the body energy [7]. The amount of glucose (sugar) present in the blood of a human, to facilitate the quantitative analysis, is represented by the term of blood glucose concentration or level. Diabetes is characterized by the body's inability to produce enough insulin (Type-1) or by the inability to properly metabolize the insulin hormone which is produced in the pancreas (Type-2). Insulin is responsible for allowing cells to absorb glucose from food.

B. Glucometry – in Helping Diabetes Patients

Glucometry is a technique of obtaining the values of concentration of glucose in peripheral or central blood. These values, expressed either in mg/dL or mM/L, have important clinical value for metabolic disorders such as diabetes mellitus, denutrition, and some of their consequences like hyperosmolar coma, malabsorption syndrome and the most critical – hypoglycemia, lower than normal level of blood glucose[3].

C. *Expected Results for people without diabetes*

Glucose measurement system is calibrated in Plasma Blood Glucose Level. Plasma Blood Glucose test Result provides output like,

Before eating < 110 mg/dL
Two hours after meals < 140 mg/dL

1) Low blood glucose (hypoglycemia) symptoms may include trembling, sweating, intense hunger, nervousness, weakness or trouble speaking.

2) High blood glucose (hyperglycemia) symptoms may include intense thirst, a need to urinate too often, a dry mouth, vomiting, or headache.

D. *Different forms of Blood glucose measurement*

Glucose measurements, more specifically blood glucose tests, are of various types according to medical science [6]. Some blood glucose measurement types are mentioned bellow-

- Plasma Glucose Fasting Blood Sugar Test
- Plasma Glucose Random Blood Sugar Test
- Plasma Glucose 1 Hour Post Parental Blood Sugar Test (PPBST-1)
- Plasma Glucose 2 Hour Post Parental Blood Sugar Test (PPBST-2)
- Plasma Glucose 75 gm Glucose Drink PPBS Test(GTT)

III. Design Methodology

The design of an effective BGM device must incorporate a wide range of functions such as sensing of the blood sample, computation to determine the glucose level in the blood, user interface to display results and control and store in memory.

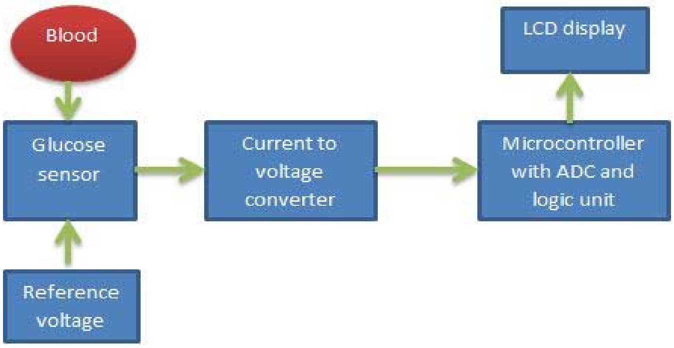

Fig. 1. Block diagram of blood glucose meter.

The block diagram of blood glucose meter is shown in Fig. 1. The measurement of glucose concentration using electrochemical test strips is completed by the following procedure:

A. *Electrochemical blood glucose test strips (EBGTS)*

At first the glucose of human blood is sensed by one kind of transducer. The electrochemical blood glucose test strip, in abbreviation EBGTS, is a very small volume disposable electrochemical cell which is contacted with sample blood. Then it produces, in conjunction with a test meter, an electrical current which is proportional to the blood glucose concentration [6]. Typical currents are a few µA.

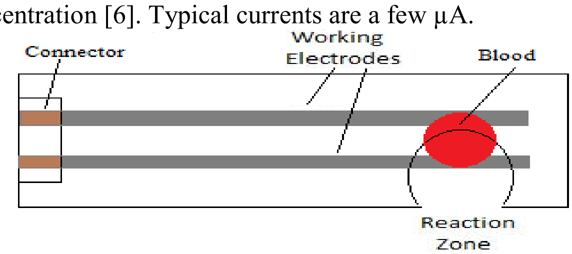

Fig. 2. Schematic diagram of test strips.

The sensor is composed of various electrodes: a glucose oxide membrane layer, a polyurethane film that is permeable by the glucose, oxygen, and hydrogen peroxide. Three electrode models are used such as working electrode (WE), reference electrode (RE), and a counter electrode (CE). But in practical way to explain ampereometry, a voltage is applied in the WE and RE electrodes with a range of -400 millivolts to 8 volts. This is used to define the voltage at which the sensor is able to perform at the maximum current.

B. *Electrochemical reaction of glucose using Enzymatic method*

This electrical current is produced by the very selective oxidation of glucose in the blood sample, which is catalyzed by two reagents which are pre-coated inside the test strip: (1) an enzyme and (2) a mediator molecule [4].

1) Enzyme: Four enzymes are commonly used in these strips and these are Glucose Oxidase, PQQ-Glucose Dehydrogenase, NAD-Glucose Dehydrogenase and FAD-Glucose Dehydrogenase [6]. Enzyme reacts directly with the glucose molecule to remove its two available electrons.

2) Mediators: A few commonly used mediators are: (a) ferricyanide, (b) 1, 10-phenanthroline Quinone, and (c) osmium-based mediators. Their oxidation potentials are 500, 100, and -120 mV (against Ag/AgCl reference), respectively [6], which takes two electrons from the enzyme, and transports them to the working electrode. Some common features of mediator are- rapid reactivity with enzyme and working electrode, capable of being easily stabilized in oxidized rate, high solubility in blood.

When a small sample of blood containing glucose is deposited on the test strip, the electrodes and the presence of the mediator, enzyme on the test strip prior to the blood reaching the electrodes, the enzyme will react with the blood glucose to create free electrons. The free electrons can be moved through a circuit when a voltage is applied between the two electrodes. Each enzyme and mediator molecule can repeat this transfer again and again, if necessary. The amount of charge that moves through the circuit will be representative of the blood glucose level in the sample. Although there are many differences between the various commercially available test strips, they all rely on the fundamental mechanism of discussed above [5].

Among the wide variety of commercially available blood glucose sensor, here, in this analysis, freestyle test strips are used. In free freestyle test strips, glucose oxidase is used as enzyme. Hence, the following electrochemical reaction will be occurred in electrodes.

$$\text{Glucose} + O_2 \xrightarrow{\text{glucose oxidase}} \text{D-glucono-1,5-lactone} + H_2O_2$$

This oxidation reaction produces a current flow. The amplitude of this current is directly related to the concentration of blood glucose. During the reaction, the concentration of glucose decreases with time due to the oxidation reaction. This decreased concentration of glucose reduce amount of current as well as voltage in the input port of MCU. Earlier, it is notable that it requires a few seconds to start reaction. This reaction time varies with the types of test strips available. When a sample is applied to the test strip, the voltage jumps to a peak value and then stabilizes between 2 and 6 seconds.

C. Relation of current & voltage with Glucose concentration

It has been formerly mentioned that the current due to oxidation reaction in EGBTS stabilizes after a few seconds. This amount of current also varies with different test strips. In this designed system, freestyle test strips are used for sensing blood glucose. The discrete values of current and glucose concentration after 5 seconds in freestyle test strip are shown in Table I [4], [6].

TABLE I: RELATION OF CURRENT AND VOLTAGE WITH GLUCOSE CONCNTRATION

Glucose (mg/dL)	Current (µA)	Voltage (Volt)
46	7	.7
71	11	1.1
97	14	1.4
130	17	1.7
162	21	2.1
198	24	2.4
246	29	2.9
297	34	3.4
349	38	3.8
393	42	4.2

For this value of output voltage depend on both current-voltage converter circuit & inverting amplifier. Using transcendental equation of fitting a non-linear equation of two variables [15], a relationship between concentration of blood glucose and final voltage output after inverting amplifier are set up.

Say, glucose concentration is represented by Y & voltage output is represented by X. So the two variable of transcendental equation relates by

$$b = \frac{n\sum \ln x_i \ln y_i - \sum \ln x_i \sum \ln y_i}{n\sum (\ln x_i)^2 - (\sum \ln x_i)^2} = 1.223$$

$$\ln a = \frac{1}{n}\left(\sum \ln y_i - b\sum \ln x_i\right)$$

a= 66.896

Finally we get, Y=66.896 * X^1.223

This is a transcendental equation. For any value of X (voltage), Y (glucose level) can be determined. So, finally the equation instead of linear one, have developed:

Concentration=66.896 * (5*ADCvalue/1024) ^1.223

IV. Proposed Design & Circuit Details

Fig. 3 depicts the proposed design flow. The whole design and circuit details are discussed in this section.

A. Current to voltage converter

The EBGTS sense the glucose concentration present in the blood sample, then produces a current proportional with the glucose concentration. This amount of current is converted to analog voltage using current-voltage converter [14].The output voltage depends on the current from test strips. In mathematically,

V1= - (input current* feedback resistance (RF1)).

Here, V1 is negatively polarized. But microcontroller can't sense negative voltage. So voltage is inverted with unity gain.

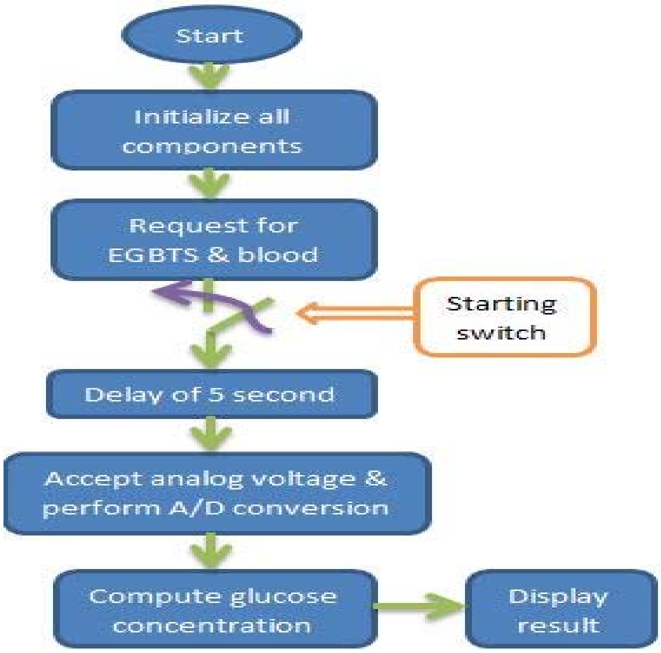

Fig. 3. Proposed Design Flow Chart.

B. Inverting amplifier

Simple but reliable op-amp inverting amplifier is used in proposed design. The gain of this scheme depends on-

$$A_v = - RF1/R1.$$

Where RF1= feedback resistance and R1= input resistance. Since, unity gain configuration is selected, so the input will be the just invert in output.

C. Microcontroller unit

Atmega8A as microcontroller unit is introduced. The Atmel AVR ATmega8 is a low-power CMOS 8-bit microcontroller based on the AVR RISC Architecture. It has internal ADC & oscillator. So cost is reduced. ATmega8 can operate in both 8 MHz & 16 MHz clock signal. Earlier mentioned that, the small current produced by the test strip rapidly changes. So the use of 16 MHz clock signal provides much accurate result [13].

The coding of designed meter is developed in C. Data type float is used. It requires four bytes of memory to store each result. Atmega8A has 512 bytes of EEPROM. Though the results are displayed in both units, but stored only the result of mg/dL for future access. So 128 result of glucose testing can be stored.

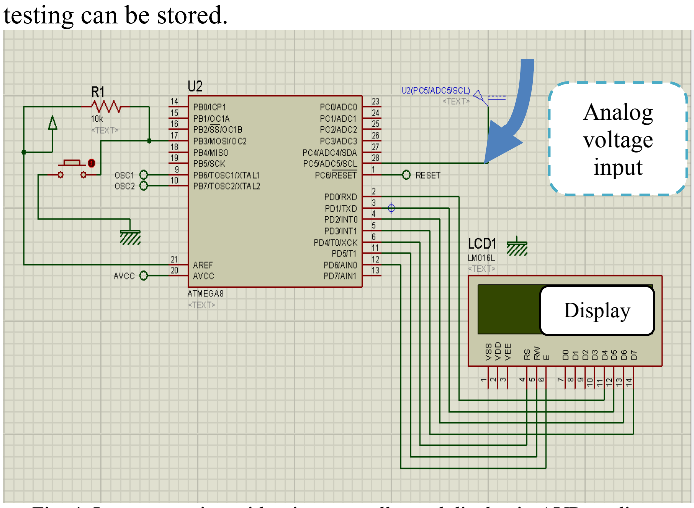

Fig. 4. Interconnection with microcontroller and display in AVR studio.

Fig. 4 shows the interconnection with microcontroller and display AVR. The microcontroller unit accepts analog voltage as input. This analog voltage is then converted into digital by the internal ADC of Atmega8A. Atmega8A has internal ADC of 10 bit. So, it can digitize any voltage between its applied reference voltages one of from 1024 level. Zero(0) volt as lower limit & 5 volt as upper limit are selected. This ADC value is then used to compute the blood glucose concentration. Then the result is displayed in monitor.

V. Result & Performance of Proposed Meter

The proposed glucometer has two main advantages over commercial glucometer. These two are cost and accuracy.

A. Cost

The cost of the proposed meter is only 400 BDT i.e. only \$5. The comparison price between commercially available meters and the proposed meter is shown in Table II. In the table, it is shown that, the proposed meter cost is only BDT 400 i.e. USD 5 whereas the available commercial glucometer price is not less than BDT 1250. So, it is clearly shown that, the proposed meter price is almost three times lesser than any commercial meter. The production cost is depicted in Table III.

TABLE II . PRICE-LIST OF COMMERCIAL GLUCOMETERS.

Glucometer Name	Price (BDT)	Price (USD) (Approximate)
E-valve	1250	15.5
Caresense-2	1900	24
Clever check	1700	21
Safe touch	1000	12.5
Glucose sure star	1500	19
Glucose sure plus	2500	31
Sense card	1800	22.5
True result	1500	19
Alcose	1400	17.5
Bionim	1300	16
PROPOSED METER	**400**	**5**

TABLE III . TOTAL COST OF GLUCOMETER

SL. No	Names	Quantity	Per Unit price (\$)	Price (\$)
1	Microcontroller	1	1	1
2	LCD Display	1	1.88	1.88
4	Op-amp	2	.1	.2
5	Resistors	6	.01	.06
7	Variable resistors	1	.06	.06
8	Switch	1	.05	.05
9	Packaging, labor & others			1.75
Total Cost				**5**

B. Accuracy

Most of the available glucometer usages linear equation to relate amount of voltage/charge generated from EBGTS depending on the glucose concentration [1], [3], [6], [7], [8], [11], [17,]. The use of linear equation increases the average deviation which is shown in Fig. 5. In Fig. 5, it is seen that most of the points are not in line and hence it increase deviations. In Fig. 6, the glucose voltage relationship using transcendental equation is shown and here it is seen that, most of the point are in line and the average deviation is much lesser than the commercial meters.

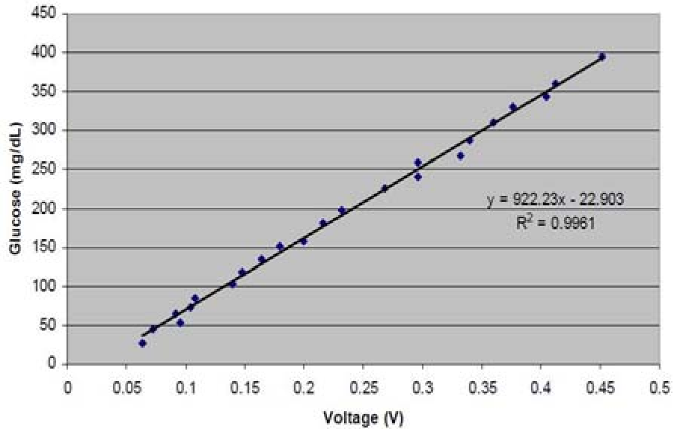

Fig. 5. Glucose-Voltage relationship using linear equation [2].

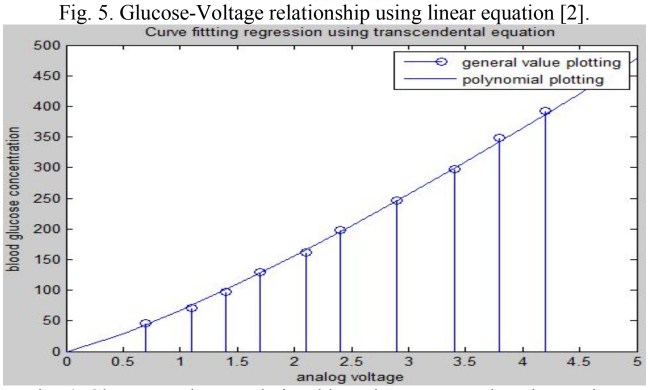

Fig. 6. Glucose-Voltage Relationship Using Transcendental Equation.

According to the Parke's error grid analysis [18], minimum average deviations of different meter system are shown in Table IV.

TABLE IV . ERROR ANALYSIS OF DIFFERENT EXISTING METER.

Meter system	Average deviation (mg/dL)
TRUEresult	9
OneTouch Ultra	12
Ascensia CONTOUR	15.7
Freestyle Freedom Lite	11.7
PROPOSED METER	**7**

The average deviation of designed meter is less than 7 mg/dL. This improvement is achieved due to the use of transcendental equation to relate voltage and glucose concentration.

To measure blood glucose level & the variable "concentration" is defined as float, so that it can hold up to six digits after decimal point but here displayed only three digits after decimal point. So round off error can be avoided. Here 1024 is due to 10 bit ADC & 5 is due to reference voltage difference. So the resolution of proposed meter is 0.341 mg/dL(ADC=100). This meter would be able to sense a change in input voltage as little as 5 mV due to 10 bit A/D converter.

As transcendental equation is used to relate voltage & glucose concentration, So the sensitivity at lower level of blood glucose concentration would be more than higher level. For example sensitivities are 0.341, 0.398, 0.436 and 0.541 mg/dL for ADC values of 100, 200, 300 and 800.

C. Performance

Some sample tests are done over 38 persons (31 Male, 7 Female) to measure the accuracy of proposed meter. The blood sample of a person is tested by designed meter and it is compared with a commercial Accucheck Glucometer along with pathological tests. Because of huge data complexity and place constraint Table V has shown the best 5 results of the test. In the table, it is seen that, the proposed meter deviation from the pathological data is much lesser than the commercial meter. The deviation of proposed meter from the pathological data is not greater than 10 in any case. In Table VI, the final specifications of the proposed meter are shown.

TABLE V. COMPARISON OF RESULTS

SL. No	Results (mg/dL)			*Deviation From Pathological Data*	
	Proposed meter	*Accucheck meter*	*Pathology test*	*Proposed meter*	*Accucheck meter*
Person-1	106.699	101	112	5.3	11
Person-2	95.502	92	104	8.5	12
Person-3	131.994	117	126	5.9	9
Person-4	121.670	126	117	4.6	9
Person-5	115.462	103	109	6.5	6

TABLE V I. PROPOSED METER SPECIFICATIONS

Parameters	Values
Result Range	52 - 480 mg/dL or 3.0-26.7 mM/L
Sample Size	0.5 microliters (0.5 µL)
Sample Type	Fresh capillary whole blood from the finger or forearm
Test Time	As little as 5 seconds
Result Value	Plasma calibrated
Assay Method	Electrochemical
Power Supply	DC 5V
Shut-off	Automatic after 30 seconds.
System Operating Range	Relative Humidity: 10 - 90% (non-condensing)
Temperature	50° - 104°F

V. CONCLUSION

In this paper, the main goal is to design and implement a very low cost with greater accuracy blood glucose meter than the conventional one. The hardware and software features of a microcontroller based system for the measurement of blood glucose are described. The necessary software is developed in C programming, using AVR studio. The system is quite successful for the measurement of blood glucose with an accuracy of around 93% which is far better than conventional meters. The cost is extremely low compared with other glucometer so that it can be beneficiary for the developing countries like Bangladesh. If the proposed meter is marketed by any industry, millions of people in developing and underdeveloped country will be benefitted.

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