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Research Article

Design of Electrodes on Gold Test Strips for Enhanced Accuracy in Glucose Measurement

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This paper reviews the practical process of designing the electrodes on electroless immersion gold-plated test strips for glucose measurement. We have found that great care must be taken on determining the width and length of the working and reference electrodes, to yield the optimum performance on electroless immersion gold-plated glucose test strips for glucose measurement. Preferably, a width of at least 0.6 mm and a length of at least 24 mm are recommended to prevent variance in electrode resistance during mass production of electroless immersion gold-plated glucose test strips, in order to enhance the accuracy of glucose measurement. This paper also recommended that, if two different geometric sizes of test strips are going to be used on the same glucose meter, both test strips must use different lengths and widths on the working and reference electrodes to yield the same electrical resistance and hence similar electrochemical performance.

1. Introduction

Electrochemical test strips for a long time have used electrodes to measure the electrical response from the electrochemical reaction while measuring the concentration of the species in the blood analytes. Most of the blood glucose tests measured the electrical current, flowing through the working and reference electrodes in the reaction zone where enzyme solution is present to react with blood glucose under fixed applied electric potential. This electrical current linearly relates to the glucose level. For the same glucose level of blood sample to be measured under same fixed applied electric potential, very close glucose readings can be obtained if there is no significant difference in electrical resistance of electrodes between different test strips. Nevertheless, different electrical currents, and hence different glucose readings, can be obtained if there is significant variance in electrical resistance of electrodes between different test strips. Therefore, the accuracy of measurement heavily depends upon the consistency in electrical resistance on the electrodes between the test strips. The most popular materials used for electrodes on the test strips nowadays are carbon/silver or carbon. Test strips with carbon/silver or carbon electrodes, mostly made by screen printing process, are notorious for the inconsistence in electrical resistance between different test strips on the same panel, different panels, and different lots. It has always been difficult to produce test strips with consistent electrical resistance on electrodes between test strips from screen printing process with carbon or silver pastes mixed with solvent. As a result, carbon test strips required codes on every vial of test strips produced to justify for the difference in electrical resistance of electrodes between test strips. The process of coding the test strips is very time consuming and tedious [1, 2]. Apart from that, many of the test strips produced were discarded because they were out of the range of codes.

Recently, to overcome the inconsistence in the electrical resistance of electrodes between different test strips in carbon/silver or carbon test strips, there are more and more glucose test strips made of palladium or gold electrodes which are more consistent in the electrical resistance of electrodes between different test strips and have been found to have better accuracy in glucose measurement. However, gold test strips are normally made of vacuum deposition or chemical etching, which is quite expensive, making it difficult to be an alternative material to replace carbon/silver test strips on the standpoint of cost saving and accuracy. This leads us to look for other gold-coated electrodes used in the printed circuit board technology, which is technologically mature, mass produced, electrically stable, and very affordable.

However, very little knowledge is available about the design criteria for the gold electrodes of test strips. It is therefore desirable to understand the design criteria of electrodes for glucose test strips and, in particular, the electroless immersion gold-plated glucose test strips, which have the most consistent electrical resistance in electrodes between test strips and the lowest cost that is price comparable to carbon/silver test strips. When the gold test strips are comparable in costs to carbon/silver test strips, we can then easily replace carbon/silver test strips with gold strips of better precision and accuracy. The reason why we choose electroless immersion gold-plated glucose test strips is that these are the only gold test strips that are as cheap as carbon/silver test strips. Yet, it is much better in accuracy and precision, particularly when considering different locations on the same panel, different panels, and different lots.

Wang and Macca [3] did some amperometric studies on carbon test strips. But, they did not do any works on gold test strips nor any works on the effect of electrode design on glucose measurement. Zeng et al. [4], Wang and Pamidi [5], Jufík et al. [6], Nouira et al. [7], Rafighi et al. [8], and Ramanavicius et al. [9] discussed gold nanoparticle deposition in carbon electrodes for enhanced performance. Hsu et al. [10] further disclosed another biosensor electrode design of gold electrodes. Kausaite-Minkstimiene et al. [11] discussed the amperometric glucose biosensor based on graphite rod (GR) working electrode modified with biocomposite consisting of poly(pyrrole-2-carboxylic acid) (PCPy) particles and enzyme glucose oxidase (GOx). Virbickas et al. [12] discussed spontaneous oxidation of Prussian white (PW), which is completely reduced form of Prussian blue (PB), has been investigated at ambient conditions and stable form of PW-PB as an intermediate oxidation state based on the presence of both redox forms (PW and PB). Kim et al. [13] studied the effect on filling pressure of enzyme solution with jetting dispenser on gold-printed circuit boards. Kim et al. [14] further discussed about the effect of dispenser height on the accuracy of gold test strips. But, none of them have discussed the design criteria for the electrodes of test strips using electroless immersion gold. Electroless immersion gold-plated printed circuit boards have been used widely on electronics devices for many decades. Chang [15] discussed the performance of gold-plated printed circuit board blood glucose test strips using ink jet printing process. Lin [16] discussed the accuracy enhancement of glucose monitoring by electrochemical approach using gold-plated printed circuit board blood glucose test strips. None of the above articles discussed the design criteria of gold electrode for better performance.

Electroless immersion gold-plated printed circuit boards have been widely used on electronic devices for many decades. However, they were first used for the measurement of glucose test strips some 15 years ago [15, 16]. The electrodes of electroless immersion gold-plated glucose test strips basically have working and reference electrodes which further consisted of three laminated layers of electrodes, namely, copper, nickel, and gold, as shown in Figure 1. The copper layer generally is a 1/2 oz copper, situated on 0.25 mm to 0.4 mm thickness of substrate of reinforced epoxy or PET. 90 to 120 μ of nickel is plated on the copper and 3 to 4 μ of gold is deposited further on the nickel by electroless immersion gold plating method. During the mass production process, different test strips will have electrodes with different widths, lengths and thicknesses of electrodes, as well as different thicknesses of copper, nickel, and gold. During glucose measurement, with fixed applied potential, variation in electrical resistance can mean different resultant currents. The blood glucose result is measured by applying fixed potential, and higher electrical resistance from electrodes of test strips will give lower current and hence lower glucose reading. Any variance in width, length, and thickness of copper, nickel, and gold between test strips can result in test strips with significantly different electrochemical performances, if the electrodes have not well designed and validated.

Since the measurement of glucose concentration is determined by the electrical current generated under fixed applied electric potential, the key issue for better accuracy of measuring glucose is to yield consistent electrical resistance between different test strips during mass production through proper design of electrodes. This can be difficult without proper understanding of the design criteria of electrodes on test strips, considering so many variables that can be present during the process of mass production, as different test strips may have variance in width, length, and thickness in electrodes, as well as variance in the thickness of copper, nickel, and gold for the electroless immersion gold-plated glucose test strips. Of course, other factors also will affect the electric current generated from the electrochemical reaction, such as the distance between working and reference electrodes, the size of working electrodes, and the thickness of the gold layer. Nevertheless, in this paper, all these variables will be fixed as the same for all test strips to prevent confusion.

The electrical resistance R for a uniform homogeneous conductor depends on the geometric properties of a sample [17] as follows:

$$R = \rho \frac{L}{A}, \tag{1}$$

where L is the length of the sample, A is the cross-sectional area, and ρ is the resistivity, measured in units of resistance times length (mΩ in SI units). Abdur Rahman et al. [18] discussed the effect of electrode geometry on the impedance evaluation of tissue and cell culture. Spragg et al., Wu, and Chandra et al. [19–21] discussed the factors that influence electrical resistivity measurements in cementitious systems. All available articles did not clearly study the design criteria for multilayer of laminated structures, particularly considering the nature of nonhomogeneous distribution of physical structure in mass production. There has been very little works done to thoroughly understand the design criteria of electrodes with the consistent electrical resistance between test strips, which consist of multilayer, laminated structure of different compositions and nature.

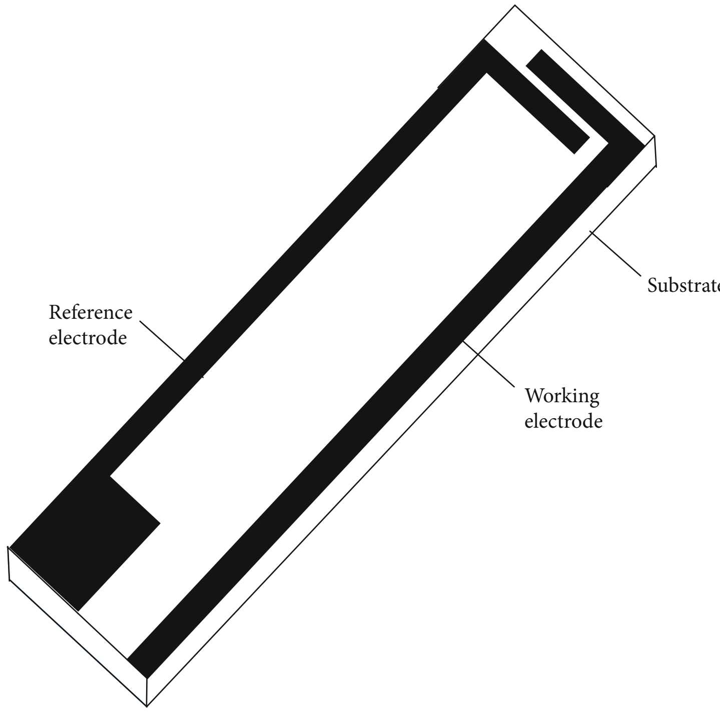

Figure 1: Schematic drawing of the electrodes on a test strip substrate.

Lee [22] revealed a gold test strip design for multiple tests on a single strip, in which a test strip contains 10 small test pieces, each test piece having its own working electrode and reference electrode, as shown in Figure 2. In this study, each small test piece has a working electrode of 7.15 mm in length and a reference electrode of 6.5 mm in length. From the standpoint of cost saving, it was practically interesting to know if we can have the test strip, shown in Figure 1, with a working electrode of 24.65 mm in length and a reference electrode of 24 mm in length, and the test strip shown in Figure 2 to work on the same glucose meter. In order to be sure if this is possible, we need to thoroughly understand the design criteria of gold test strip electrodes.

1.1. Experimental. Figure 3 shows the schematic drawing of the electrodes, showing the width and length of the working and reference electrodes. The length is defined as the distance between the geometric center of the contact pads with the glucose meter and the geometric center of the working electrode or reference electrode inside the reaction zone for enzyme reaction, as shown by the X marking. $L1$ ($L1$A+L 1B) is defined as the length of the reference electrode, and L 2 ($L2$A+$L2$B) is defined as the length of the working electrode for use in this study and W is the width of the working electrode and reference electrode. $L1$B and $L2$B are the always the same throughout this study, while $L1$A, $L2$A, and W can be different. Three lots of test strips with four different lengths and four different widths of electrodes, working electrode, or reference electrode were randomly used for the study. The width of the working electrode is defined as the same as the reference electrode for all 4 different widths. Four combination of different lengths and widths of reference electrodes and working electrodes are given in Tables 1 and 2. The distance between working electrode and reference electrodes is always 0.35 mm. Three lots of test strip panels, in which each panel contained hundreds of 16 different types of test strips, are from the same manufacturer who prepared the samples under the same processing procedures. The surface of test strip panels was well cleaned to remove possible residual chemicals from the manufacturing process. The purpose of this study is to determine the optimum width and length of electrodes to allow for possible variance in size during mass production, which does not significantly affect the electrical resistance of the electrodes and hence does not significantly affect the glucose readings.

We measured the electrical resistance with PXI-4130 Source Measure Unit from National Instrument, following the Kelvin (4-wire) Resistance Measurement method to measure only the resistance of the electrode [17], as shown in Figure 4. 30 test strip samples of each batch were used for the measurement for each of the 16 conditions. All test strips used 1/2 oz copper, deposited with 80 μ to 120 μ thickness of nickel and 3 μ to 4 μ of gold by electroless immersion gold plating process, and every test strip had different thicknesses of nickel and gold. Glucose oxidase (GOD) solutions, same as the GOD formulation used by Joinsoon Medical Technology (JMT) glucose monitoring systems, were deposited onto the reaction zone over the working and reference electrodes for the control solution tests. The test strips were tested by 10 JMT Glucose Meters with data port linked to computer for data acquisition and further verification. The JMT Glucose Monitoring Systems were certified by CE and US FDA. YSI (Yellow Spring Instrument) Stat 2300 was used to verify the glucose readings of the

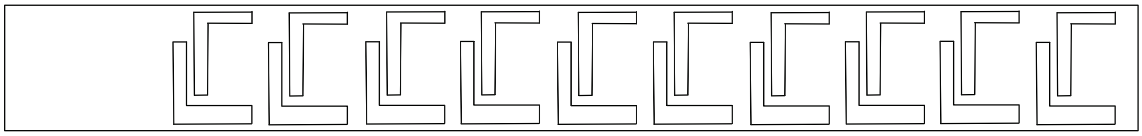

Figure 2: Schematic drawing of a gold test strip design for multiple tests on a single strip [20].

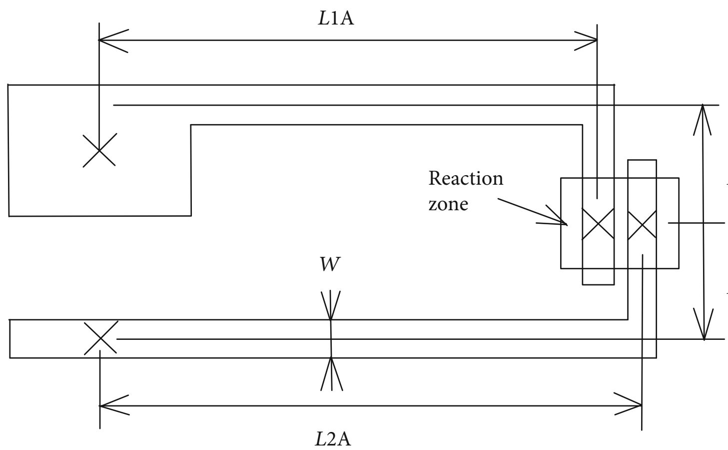

Figure 3: Schematic drawing of the electrodes to show the position of measuring the electrical resistance for the working and reference electrodes.

Table 1: Four different lengths $L1$ and width W of reference electrodes were used for the experiment in this study.

Reference electrode length (mm)/electrode width (mm)			
24/0.206	24/0.426	24/0.62	24/0.77
15/0.206	15/0.426	15/0.62	15/0.77
10.4/0.206	10.4/0.426	10.4/0.62	10.4/0.77
6.5/0.206	6.5/0.426	6.5/0.62	6.5/0.77

Table 2: Four different lengths $L2$ and width W of working electrodes were used for the experiment in this study.

Working electrode length (mm)/electrode width (mm)			
24.65/0.206	24.65/0.426	24.65/0.62	24.65/0.77
15.65/0.206	15.65/0.426	15.65/0.62	15.65/0.77
11.05/0.206	11.05/0.426	11.05/0.62	11.05/0.77
7.15/0.206	7.15/0.426	7.15/0.62	7.15/0.77

test strips to compare with the reading displayed by the JMT Glucose Meters.

$$R_{\text{subject}} \frac{\text{Voltmeter indication}}{\text{Ammeter indication}}. \tag{2}$$

2. Results and Discussions

The actual electrical resistance from production panels of electroless immersion gold-plated glucose test strips is shown in Figure 5. Figure 5 shows the relationship between the average electrical resistance and the electrode length of the reference electrode for electrode widths of 0.77 mm, 0.64, 0.426, and 0.206 mm, respectively. From Figure 5, the average electrical resistance is the average of 30 test data, which increases linearly with the electrode length, while reducing the width of electrodes increases the average electrical resistance for the same electrode length. When the electrode length is small, the average electrical resistance between electrodes of different widths is not much different. However, as the electrode length increases, the difference in average electrical resistance between electrodes of different widths increases. From the practical points of view, it is not easy to produce electrodes of significantly different lengths without being identified through visual inspection, but it is more likely to produce electrodes with different widths during mass production process. Therefore, we should pay more attention to the change of electrical resistance of reference electrodes with the electrode width. The interpolation of the straight line in Figure 5 did not go through the origin, possibly because that $L1$ contains $L1A$ and $L1B$ and that only $L1A$ varies while $L1B$ remains the same.

Figure 6 shows the relationship between the average electrical resistance and the electrode width of the reference electrode for electrode lengths of 24, 15, 10.4, and 6.5 mm, respectively. From Figure 6, the average electrical resistance is the average of 30 test data, which increases with the electrode length, while increasing the width of electrodes decreases the average electrical resistance for the same electrode length.

In order to understand the possible variance in electrical resistance among the test strips produced, we further studied the CV (coefficient of variation) of the electrodes. CV is defined as the ratio of standard deviation over the average

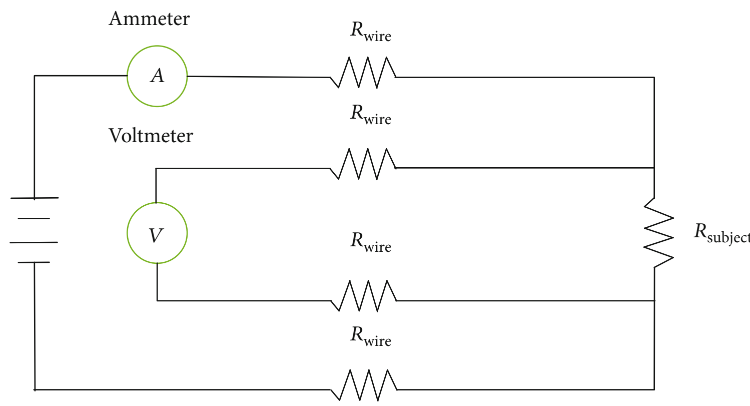

Figure 4: Schematic drawing of the Kelvin (4-wire) Resistance Measurement method to measure the electrical resistance of the electrodes.

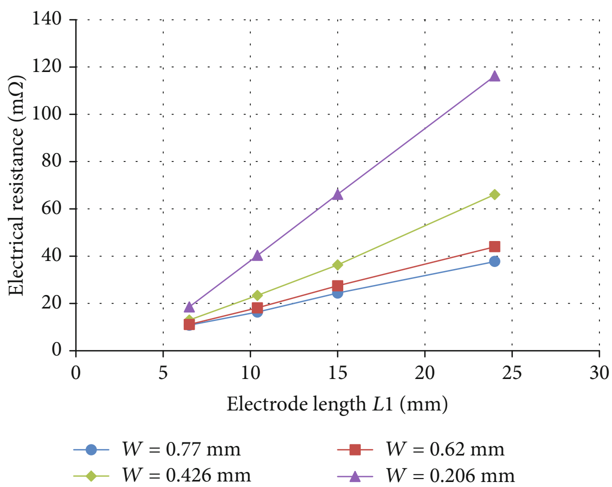

Figure 5: The relationship between the average electrical resistance and reference electrode length for 4 different reference electrode widths.

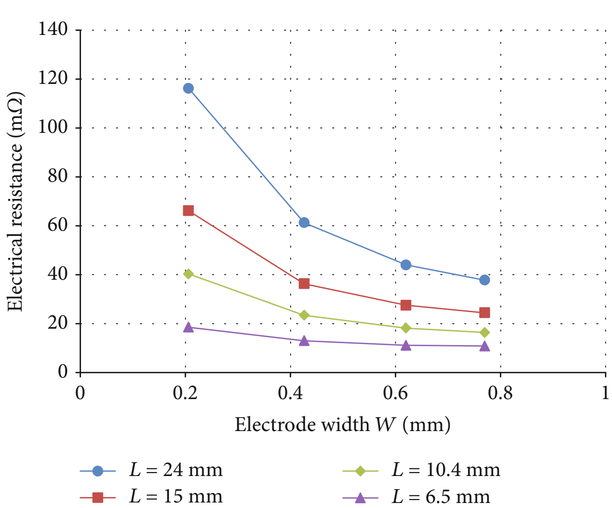

Figure 6: The relationship between the average electrical resistance and reference electrode width for 4 different reference electrode lengths.

and is widely used to study the variance in physical properties. By summarizing the test results, we have obtained the test data shown in Figure 7, which is the CV in electrical resistance against reference electrode length for different reference electrode widths. For the same width of 0.77, the increase in electrode length decreased the CV. This means that wider electrodes can have more variation in electrical resistance on the electrodes. More narrow electrodes seemed to have less CV or variation in electrical resistance. From Figure 7, it clearly shows that when the electrode width is 0.206 mm, changing the length of the electrode does not change much the CV of electrical resistance. The CV is from 1.98% to 2.53%. However, when the electrode is 0.77 mm, changing the length of the electrode significantly changes the CV of electrical resistance. The CV is from 1.77% to 10.33%. It seems that there is a limit for the design of electrode geometry beyond which the variation will get higher. As a result, great care must be taken when designing the electrodes.

These CV results were obtained from test strip samples out of the production panels of test strips. Through proper quality management over the production process, there is likely a chance to further reduce the CV to lower figures. Unlike the CV shown in Figure 7, the electrical resistance test results shown in Figures 5 and 6 are intrinsic in nature. They cannot be changed by the manufacturing process parameters.

Similar to Figure 5 for the reference electrode, Figure 8 shows the relationship between the average electrical resistance of the working electrode and electrode length for 4 different electrode widths. Since all the working electrodes are 0.65 mm longer than the reference electrodes for the test strip sample used in this study, therefore, Figure 6 will be similar to Figure 9, and Figure 7 will be similar to Figure 10. The interpolation of the straight line in Figure 8 did not go through the origin, possibly because that $L2$ contains $L2$A and $L2$B and that only $L2$A varies while $L2$B remains the same.

Between test strips, we do not want to have variation in electrical resistance due to possible variation in size of electrodes. From Figures 6 and 9, it seems that for reference electrode width over 0.6 mm, the electrical resistance will be more stable, less likely to change significantly with possible variation in width from mass production. Furthermore, if we look at Figures 7 and 10, longer electrodes had lower

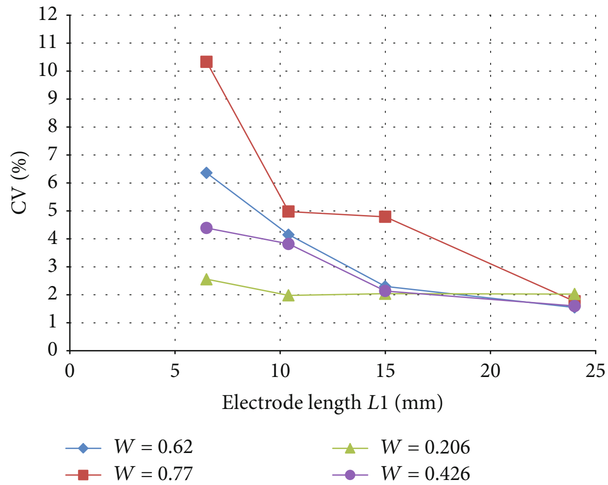

FIGURE 7: CV in electrical resistance against electrode length for different reference electrode widths for the reference electrodes.

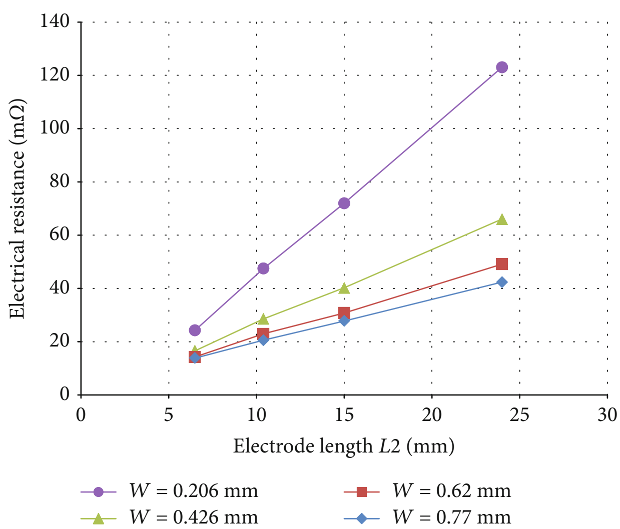

FIGURE 8: The relationship between the average electrical resistance of the working electrode and electrode length for 4 different electrode widths.

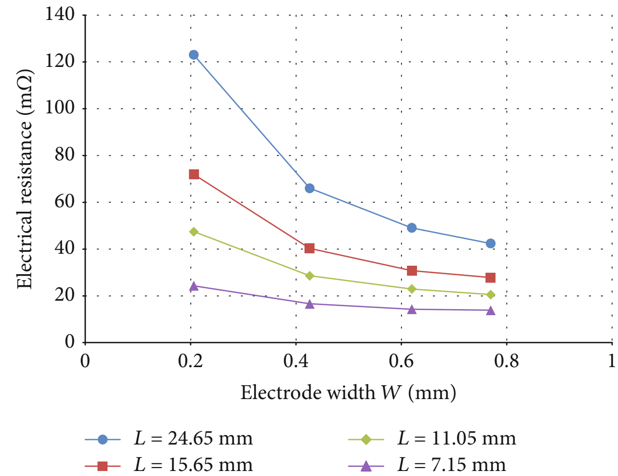

FIGURE 9: The relationship between electrical resistance of the working electrode and electrode width for 4 different electrode lengths.

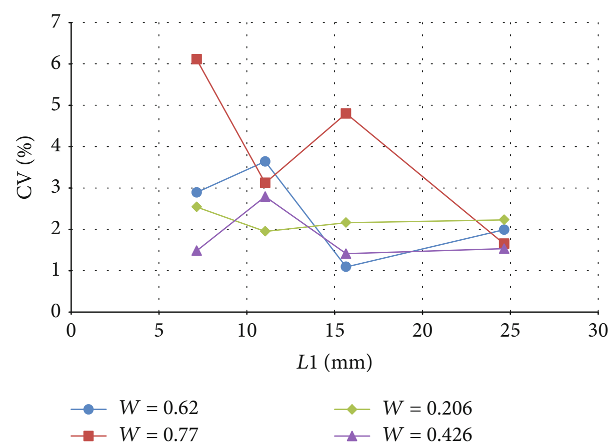

FIGURE 10: CV in electrical resistance against working electrode length for different working electrode widths.

CV in electrical resistance. Although, it seems that from Figures 7 and 10, an electrode width of 0.206 mm has lower CV than the other conditions at various electrode lengths from 6.5 mm to 24 mm or from 7.15 mm to 24.65 mm. Although these results looked promising from the standpoint of cost saving, nevertheless, it is too early to conclude based on the preliminary test data obtained just from only 3 lots of gold test strips, which were produced and monitored under very careful conditions, without considering the complicated nature of gold plating processes that often was contaminated with less demanding electronic devices. Especially from Figures 6 and 9, considering the fact that the electrical resistance increased significantly as the electrode width approaches 0.206 mm, it can be more risky to produce electrodes approaching 0.206 mm, particularly when the concentration of nickel and gold ions fluctuates very frequently within the batch solution when performing immersion gold plating. Therefore, for the electroless immersion gold test strips of the present study, either reference electrodes or working electrodes must have at least 0.6 mm in width and 24 mm in length for more consistency in electrical resistance. This can be controversial to production requirements. In real production, to reduce costs on electroless immersion plating of gold strips, the manufacturers like to design electrodes with a width as narrow as possible to reduce production cost, sometimes using electrodes of 0.10 to 0.12 mm in width. This can be disastrous and serious mistakes can occur without proper understanding of the geometrical factor associated with this study.

Figures 7 and 10 seem to imply that longer and wider electrodes will have better performance than shorter and more narrow electrodes. In order to validate the effect of design of electrodes on the performance of glucose measurement, Tables 3 and 4 give the results of comparisons for test strips of different lengths and widths, respectively, to

Table 3: Control solution test results from 3 lots of test strips with same electrode length but different electrode widths W (unit: mg/dL).

Length = 24 and 24.65 mm; width = 0.206 mm	Average	75.4	184	234.1	328.8	412.2	543.6
	Standard deviation	3.16	6.28	7.38	10.73	8.52	13.43
	CV (%)	4.19	3.41	3.15	3.26	2.07	2.47
	YSI	74	185	233	326	411	548
Length = 24 and 24.65 mm; width = 0.77 mm	Average	74.2	184.8	233.4	327.2	410.4	546.3
	Standard deviation	2.29	3.44	5.20	7.65	5.33	8.43
	CV (%)	3.09	1.86	2.23	2.34	1.30	1.54
	YSI	74	185	233	326	411	548

Table 4: Control solution test results from 3 lots of test strips for different electrode lengths but same electrode width (unit: mg/dL).

Length = 6.5 and 7.15 mm; width = 0.206 mm	Average	75.4	184	234.1	328.8	412.2	543.6
	Standard deviation	3.16	6.28	7.38	10.73	8.52	13.43
	CV (%)	4.19	3.41	3.15	3.26	2.07	2.47
	YSI	74	185	233	326	411	548
Length = 24 and 24.65 mm; width = 0.206 mm	Average	72.8	183.8	238.9	333.9	415.4	557.6
	Standard deviation	1.80	4.95	5.27	8.30	6.25	11.38
	CV (%)	2.47	2.70	2.21	2.49	1.50	2.04
	YSI	74	185	233	326	411	548

Table 5: Control solution test results for different electrode lengths and widths (unit: mg/dL).

Length = 10.5 and 11.05 mm; width = 0.206 mm	Average	73.7	182.5	230.4	327.7	412.7	547.6
	Standard deviation	3.73	4.61	7.18	11.12	10.28	12.24
	CV (%)	5.05	2.53	3.11	3.39	2.49	2.24
	YSI	74	185	233	326	411	548
Length = 24 and 24.65 mm; width = 0.62 mm	Average	73.2	185.6	233.7	329.6	409.7	544.4
	Standard deviation	3.34	5.55	7.30	11.47	7.65	12.10
	CV (%)	4.57	2.99	3.12	3.48	1.87	2.22
	YSI	74	185	233	326	411	548

determine the effect of electrode design on test strip performance. Glucose readings from the glucose meters are converted values from the electric current generated from the electrochemical reaction by built-in software parameters inside the glucose meters. Different lengths and widths of electrodes have different electrical resistances and hence produce different glucose readings directly from the glucose meter. Test strips of higher electrical resistance will yield lower electrical current and lower glucose reading. Since during the glucose measurement, the glucose meters were connected to a computer for data acquisition; we can easily justify the glucose readings to make them higher or lower to make them close to the YSI values, without changing the accuracy or CV.

In order to compare the effect of electrical resistance of electrodes on glucose readings, we performed control solution tests on the gold test strips. Please note that all the glucose meters used for the tests were calibrated with the software parameters obtained from test strips with 24 and 24.65 mm and width = 0.206 mm, to make the glucose readings close to YSI. Three lots of gold test strips with 25 gold test strips for each lot were used for the tests. From Table 3, it looks like that the test strips with length = 24 and 24.65 mm and width = 0.206 mm had higher electrical resistance than the test strips with 24 and 24.65 mm and width = 0.77 mm and hence slightly lower glucose readings. From the test results shown in Table 3, it was quite likely that increasing the width of electrodes enhances the accuracy of glucose measurement. Furthermore, from Table 4, which compared the test strips with length = 6.5 and 7.15 mm, width = 0.206 mm with the test strips with length = 24 and 24.65 mm, width = 0.206 mm. From Table 4, it seems the test strips with length = 6.5 and 7.15 mm have similar glucose readings and lower CV than test strips with length = 24 and 24.65 mm. Tables 3 and 4 confirm the previous finding that gold test strips with longer electrodes with length = 24 and 24.65 mm are preferred for better accuracy. The widths of electrodes do not seem to affect much the accuracy from the control solution test results. These results support the claim that proper design of the electrodes on electroless immersion gold-plated glucose test strips could possibly improve the accuracy of glucose measurement. In Table 4, it seems that some test data are far away from the YSI readings. This is not an issue, as the readings can be justified with software parameters in the glucose meters, after the design of electrodes is determined.

There are occasions when glucose test strips of two different geometries will be used on the same glucose meter, for example, a shorter test strip with reference electrode length of 6.5 mm and working electrode length of 7.15 mm and another longer test strip with reference electrode length of 24 mm and working electrode length of 24.65 mm. Therefore, it is important to understand the effect of electrode width on the glucose reading for the same electrode length, as well as the effect of electrode length on glucose reading for the same electrode width. Table 5 clearly shows that the electrical resistance on the electrodes does affect significantly the glucose readings. In order for two different sizes of test strips to yield close glucose readings, both test strip electrode layouts must be properly configured. From Figure 6, it looks like that for reference electrode length of 24 mm, as the electrode width is at 0.62 mm, the electrical resistance will be about 43 mΩ, which can never be achieved by the reference electrode length of 6.5 mm with any width. Nevertheless, for reference electrode length of 10.4 mm, a width of around 0.2 mm can have an electrical resistance of 43 mΩ. Comparing the control solution test results from a test strip with reference electrode length of 24 mm and width of 0.62 mm, with a test strip with reference electrode length of 10.5 mm and width of 0.2 mm, the comparison is now given in Table 5 to show quite close readings between both test strips. This means that if the electrical resistance between different test strips can be well monitored to be consistently close, the glucose readings from the different test strips can be relatively close as well.

3. Conclusions

For electroless immersion gold-plated glucose test strips, it is important to properly design the electrodes, in order to keep the variation of electrical resistance between test strips as low as possible during mass production. From this study, we have found that the width of the electrodes should better be over 0.6 mm and the length of the electrodes should better be over 24 mm, for the conditions of test strips used in this study. We also have found that proper design of the electrodes on electroless immersion gold-plated glucose test strips could enhance the accuracy of glucose measurement. When making two different geometric sizes of test strips to work properly on the same glucose meter, the length and width of the electrodes of each test strip type must be properly designed to produce similar electrical resistance in order to yield close glucose test results.

Data Availability

The data used to support the findings of this study are included within the Supplementary Information File.

Conflicts of Interest

The authors declare that they have no conflict of interest.

Supplementary Materials

Table A1 shows the electrical resistance for different reference electrode lengths of 24 mm, 15 mm, 10.4 mm, and 6.5 mm, when the electrode width W is 0.77 mm (unit: mΩ). Figure 5 shows the relationship between the average electrical resistance and reference electrode length for 4 different reference electrode widths. Figure B1 shows the relationship between electrical resistance of the electrode and electrode length when the reference electrode width is 0.77 mm. Table A2 shows the electrical resistance for different reference electrode lengths of 24 mm, 15 mm, 10.4 mm, and 6.5 mm, when the electrode width is 0.62 mm (unit: mΩ). Figure B2 shows the relationship between electrical resistance of the electrode and electrode length when the reference electrode width is 0.62 mm. Table A3 shows the electrical resistance for different reference electrode lengths of 24 mm, 15 mm, 10.4 mm, and 6.5 mm, when the electrode width is 0.426 mm (unit: mΩ). Figure B3 shows the relationship between electrical resistance of the electrode and electrode length when the reference electrode width is 0.426 mm. Table A4 shows the electrical resistance for different reference electrode lengths of 24 mm, 15 mm, 10.4 mm, and 6.5 mm, when the electrode width is 0.206 mm (unit: mΩ). Figure B4 shows the relationship between electrical resistance of the electrode and electrode length when the reference electrode width is 0.206 mm. Table C1 shows the electrical resistance for different reference electrode widths of 0.206 mm, 0.426 mm, 0.62 mm, and 0.77 mm, when the electrode length $L1$ is 24 mm (unit: mΩ). Figure D1 shows the relationship between electrical resistance of the electrode and electrode width when the reference electrode length $L1$ is 24 mm. Table C2 shows the electrical resistance for different reference electrode widths of 0.206 mm, 0.426 mm, 0.62 mm, and 0.77 mm, when the electrode length $L1$ is 15 mm (unit: mΩ). Figure D1 shows the relationship between electrical resistance of the electrode and electrode width when the reference electrode length $L1$ is 24 mm. Table C2 shows the electrical resistance for different reference electrode widths of 0.206 mm, 0.426 mm, 0.62 mm, and 0.77 mm, when the electrode length $L1$ is 15 mm (unit: mΩ). Figure D3 shows the electrical resistance for different reference electrode widths of 0.206 mm, 0.426 mm, 0.62 mm, and 0.77 mm, when the electrode length $L1$ is 10.4 mm. Table C4 shows the electrical resistance for different reference electrode widths of 0.206 mm, 0.426 mm, 0.62 mm, and 0.77 mm, when the electrode length $L1$ is 6.5 mm (unit: mΩ). Figure D4 shows the electrical resistance for different reference electrode widths of 0.206 mm, 0.426 mm, 0.62 mm, and 0.77 mm, when the electrode length $L1$ is 6.5 mm. Table E1 shows CV on electrical resistance for reference electrodes with various lengths and widths (unit: %). Table F1 shows the electrical resistance for different working electrode lengths of 24.65 mm, 15.65 mm, 11.05 mm, and 7.15 mm, when the electrode width W is 0.77 mm (unit: mΩ). Figure G1 shows the electrical resistance for different working electrode lengths when the electrode width W is 0.77 mm. Table F2 shows the electrical resistance for different working electrode lengths of 24.65 mm, 15.65 mm, 11.05 mm, and 7.15 mm, when the electrode width W is 0.62 mm (unit: mΩ). Figure G2 shows the electrical resistance for different working electrode lengths when the electrode width W is 0.62 mm. Table F3 shows the electrical resistance for different working electrode lengths of 24.65 mm, 15.65 mm, 11.05 mm, and 7.15 mm, when the electrode width W is 0.426 mm (unit: mΩ). Figure G3 shows the electrical resistance for different working electrode lengths when the electrode width W is 0.426 mm. Table F4 shows the electrical resistance for different working electrode lengths of 24.65 mm, 15.65 mm, 11.05 mm, and 7.15 mm, when the electrode width W is 0.206 mm (unit: mΩ). Figure G4 shows the electrical resistance for different working electrode lengths when the electrode width W is 0.206 mm. Table H1 shows the electrical resistance for different working electrode widths of 0.206 mm, 0.426 mm, 0.62 mm, and 0.77 mm, when the electrode length is 24.65 mm (unit: mΩ). Table H2 shows the electrical resistance for different working electrode widths of 0.206 mm, 0.426 mm, 0.62 mm, and 0.77 mm, when the electrode length is 15.65 mm (unit: mΩ). Table H3 shows the electrical resistance for different working electrode widths of 0.206 mm, 0.426 mm, 0.62 mm, and 0.77 mm, when the electrode length is 11.05 mm (unit: mΩ). Figure I3 shows the electrical resistance for different working electrode widths when the electrode length is 11.05 mm. Table H4 shows the electrical resistance for different working electrode widths of 0.206 mm, 0.426 mm, 0.62 mm, and 0.77 mm, when the electrode length is 7.15 mm (unit: mΩ) Figure I4 shows the electrical resistance for different working electrode widths when the electrode length is 7.15 mm. Table J1 shows CV on electrical resistance for reference electrodes with various lengths and widths (unit: %). Table K1 shows the control solution test results for reference electrode length of 24 mm and working electrode length of 24.65 mm. $W = 0.206$ mm (unit: mg/dL). Table $L1$ shows the control solution test results for reference electrode length of 6.5 mm and working electrode length of 7.15 mm. $W = 0.206$ mm (unit: mg/dL). Table M1 shows the control solution test results for reference electrode length of 24 mm and working electrode length of 24.65 mm. $W = 0.62$ mm (unit: mg/dL). Table M2 shows the control solution test results for reference electrode length of 10.4 mm and working electrode length of 11.05 mm. $W = 0.206$ mm (unit: mg/dL). *(Supplementary Materials)*

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