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A Simple and Low Cost OP-AMP Based Instrument for Bipolar Junction Transistor I-V Curve Characterization

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Abstract

Bipolar Junction Transistor (BJT) is an electronic device made of semiconductor material. It has several functions including a switch or an amplifier. Usually, the voltage and current (I-V) characteristics is available in the datasheet issued by the producer. However, the value is still in the form of range. Hence, to get an actual I-V curve characterization, an electronic device such as a curve tracer is used to test the BJT. The testing process is usually conducted manually and requires a lot of time. An I-V characterization device that is able to record data automatically is mostly expensive. Therefore, this research aims to produce good quality automatic I-V curve characterization instrument with a lower price. The instrument has a controlled bipolar voltage source with DC output of -9.9V - + 9.9V and a controlled bipolar current source with DC output -189µA - 189µA. The current sensor uses a transimpedance amplifier instrumentation circuit or more familiarly known as I to V converter. The current sensing is able to measure -25mA - + 22mA with 98% accuracy. Besides BJT, the instrument is also capable to characterize the IV characteristic of other electronic devices such as resistor and diode. The measurement data acquisition is controlled by an Arduino Due microcontroller and displayed in Microsoft Excel connected to microcontroller by Parallax data acquisition software. This instrument is expected to answer the need of good quality automatic I-V characterization device with a good price.

Keywords; *BJT, Controlled Bipolar Current and Voltage Source, Current Measurement, I-V curves*

I. INTRODUCTION

In the present time, BJT is used as a teaching and research material in universities, especially in electronic field departments. The studies usually relate to the characterization of the I-V curve owned by the BJT. In their studies, students and laboratory assistants still commonly use makeshift tools such as multimeters, external power, and manual recording. The use of such tools is very time consuming, consequently making it more difficult for students to explore what the BJT can do. For this reason, we need a device that is able to provide a current source on the base terminal as a gate to open the collector and emitter current, the voltage source on the collector and emitter terminal, and the current sensor to read the current flows on emitter. The results are plotted on the I-V characterization graph. The device is commercially available with the name Keithley 2400. It is a voltage source, current source, voltage sensor, and current sensor with a range of 1pA - 1A. It can also plot the measurement results of these currents on the I-V curve automatically [6]. Unfortunately, these devices are still sold at a very high price.

There are also cheap curve tracers sold in the market as an adapter for X-Y oscilloscope that we need an oscilloscope to display the measurement result. Another curve tracer that sold as an integrated

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instrument with inner source, switches and X-Y display is still relatively expensive. Previous research produced a subnano-amperemeter measuring device that can measure currents with a range of 100pA - 14mA [3], also I-V meters that has a measurement range of 100pA – 3.5mA and uses logarithmic amplifier chip for Field Effect Transistor (FET) characterization with accuracy reaching 98% [2]. However, the device has not been able to measure BJT due to the need of integration with controlled current sources, also the use of logarithmic amplifier chip(LOG112) is still quite expensive.

As a result, came the idea to create an instrument that is able to provide a bipolar voltage source, a current source, and also a current sense system that is able to measure positive or negative currents with an order of 100µA. This instrument has been completed and is able to measure several electronic components such as resistors, diodes, and also BJT with an accuracy level of 98%. For data acquisition, this instrument uses an Arduino Due microcontroller that has a data processing speed of 84MHz and 12bit for each ADC and DAC pin [4]. To display measurement data, the data that has been acquired by Arduino Due will be sent via Arduino Due serial communication to PC / Laptop which will later be displayed in Microsoft Excel. And to connect Microsoft Excel with serial Arduino due, an external application called Parallax Data Acquisition is needed. This application is an open-source application that can be downloaded and used for free. All being well, this research will make it easier for students, lab assistants, and also lecturers to conduct learning and research on BJT specifically to obtain the I-V curve.

II. INSTRUMENT DESIGN

a) System Design

The instrument includes 2 bipolar power supplies which both have -15V and + 15V output, a voltage source from the Arduino DAC with output 0 - 3.3V reinforced using a differential amplifier with output -9.9 - + 9.9V, a current source with output -189.9 – 189.9µA, and a current sensor using Transimpedance Amplifier circuits or well known as I to V Converter that has the ability to read -25 - + 22mA with the value of voltage conversion of -12.5V - 11V. This instrument has an Arduino Due microcontroller with 85 MHz data speed processing and 12-bit resolution, which means thateach ADC pin has a value of 4095 with output and maximum reading of 3.3V [4]. As a result, the instrument's current reading resolution reaches 8µA. Since Arduino Due can only allow voltages up to 3.3V, the output from I to V Converter will be attenuated with 2 attenuator circuits. The first circuit is used to attenuate the positive current which means using a Voltage Divider and Voltage Buffer circuit. The second circuit inverts attenuation circuit to reduce the negative current. Attenuation value of both circuits are 5 times or Vo=0.2Vi. All of these components have been tested using Sanwa CD771 Multimeter with the current sensing ability up to 0.1µA and Rigol DP832 Power Supply which has the ability to produce electric current with a resolution of 1mA [8],[9]. The scheme of the developed instrument is shown in Figure 1.

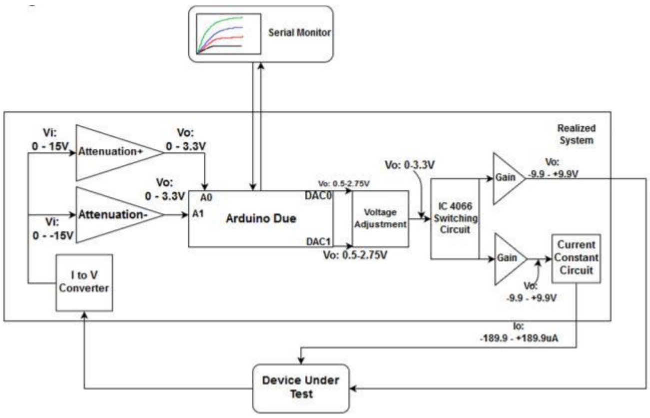

Fig. 1. Scheme of the developed instrument for device testing.

Output from Arduino Due DAC is given to the voltage adjustment circuit to adjust the 0.5-2.75V DAC output to 0-3.3V and to the IC4066 switching circuit to select which pin on differential amplifier has the output from the voltage adjustment circuit or

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whether it will be given to ground. The differential amplifier is used for voltage source and current source input gain. Voltage source will have a direct output from the first differential amplifier with a value of -9.9V-+9.9V, meaning the differential amplifier has 3 times value of gain. On the current source, the output from differential amplifier will be consigned to the constant current circuit with an output range of -189µA - +189µA. Both voltage and current sources are allotted to the tested electronic device as an input, and the current from the tested device will be given to the current sensing circuit. First is the I to V converter that converts current input to be an OP-AMP voltage output with a value of the power supplies' maximum range, that is -15V and +15V. To lower the value from I to V converter, 2 attenuator circuit will perform attenuation for 5 times. The first attenuator is used for a positive voltage output that uses a voltage divider followed by a voltage buffer circuit. The second attenuator is used for a negative voltage output that uses an inverting attenuator circuit. So theoretically, the output from the attenuator reaches 0 - 3V which Arduino Due can accept and read using the inner ADC. All of the signal conditioning circuits use OP07 OP-AMP which cuts down manufacturing costs.

B. Current Source

Constant current source is a current source that has no change of value even if we apply different value of loads. BJT needs a current input to change the depletion area so thecurrent would flow from the collector to the emitter. The NPN type BJT needs a source of positive current and the PNP type BJT needs a source of negative current. The scheme of the constant current circuit is shown in the Fig.2.

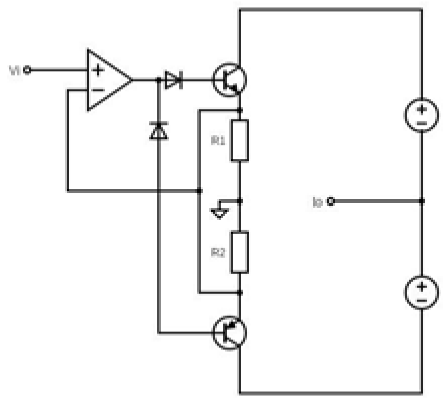

Fig. 2. Constant current circuit.

Constant current circuit is has an OP-AMP, NPN and PNP BJTs, 2 Resistors, and a series of power supply to draw current from the collector to the emitter. The OP-AMP works as a voltage buffer to acquire the voltage input. In this instrument, the input comes from a differential amplifier output voltage with a value of -9.9V - +9.9V. The OP-AMP output terminal is connected to diodes that select which BJT will be activated. If positive voltage input is applied, the NPN BJT will be active and the PNP will be inactive due to the current from the output terminal not going to the PNP BJT. If the input is negative, the NPN BJT will be inactive and PNP BJT is active. 2 resistors are needed to limit the current output and the connection of the resistor above is parallel. The value of both resistors are 100kΩ, which means the current source system has a 50kΩ resistance. From the explanation above, the equation of the current source system is as shown below.

Rp is the parallel resistance value from the system with the value of 50kΩ. The negative sign appears due to the direction of the current when either NPN or PNP BJT is active. When the NPN BJT is activated, the current will flow with the direction of its collector to the emitter. The direction of the current flow is opposite from the current source port. When the PNP BJT is activated, the current will flow in the same direction as the current source port. The output from the differential amplifier is -9.9V-

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+9.9V, so theoretically the Io will possess a value of -189µA-+189µA. To get a real characteristic of the current source, a linearity test with Arduino Due DAC value is needed. The current source will be tested with Arduino Due DAC value of 0 – 4000 with 100 value of resolution. The current source output will be read by Sanwa CD771 multimeter, which has ability to sense the current up to ±0.1µA. Results of the test is shown in Fig.3

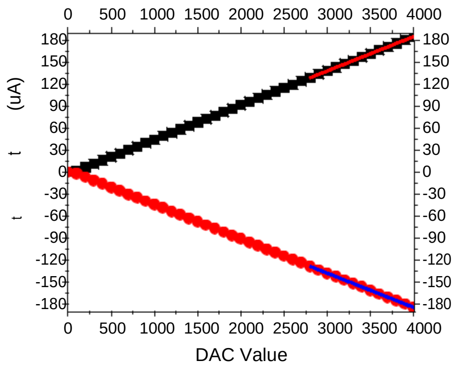

Fig. 3. Linearity test result of the current source.

Result of the test shows a graph with a 0.04µA slope at the positive current source and a -0.04µA slope at the negative current source. The adjusted R^2 value of the two sources is 0.99993, which means the two graphs are very close to the linear graph. The standard error value of both sources is 0.06nA or 0.13% at each point. The concern is the error value that appears in the decimal value of 100 - 500 would cause the graph to be slightly less linear. It causes an error as the value of 100 - 500 has a small differential amplifier output value of 0.24 - 1.21 V. The output will later be smaller on the OP-AMP output terminal which has 2 diodes with an active threshold of -0.7 - + 0.7V. However, with an error value of only 0.13% and R2 = 0.99993, it can be concluded that the current source in the system is feasible to be used in the measurement system.

C. Current Sense

There are 2 main circuits for the current sensing in this instrument. The first circuit is the I to V Converter and the second one is the Attenuator circuit. The transimpedance amplifier or well-known as I to V converter only uses OP07 OP-AMP and a sensing resistor to convert the current to OP-AMP voltage output. I to V converter circuit is shown in Fig. 4.

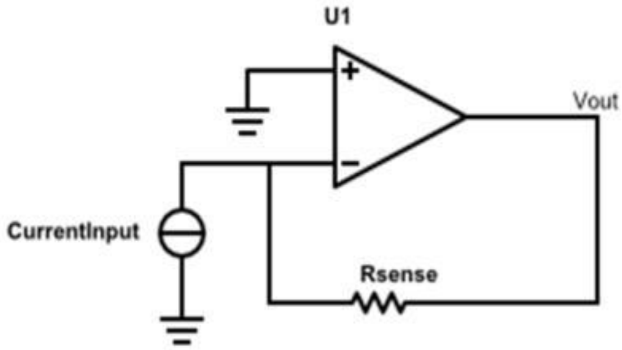

Fig. 4 Transimpedance Amplifier Circuit.

As the figure shown above, the Current Input will only go to the Rsense and not the inverting pin of the OP-AMP due to the OP-AMP characteristic that has infinite impedance input [1]. We could simply write the equation of the Vout with the OHM's law of electricity below [7].

The negative sign appears in the equation due to the current being connected to the inverting input at the OP-AMP. In this instrument 500ΩRsense is applied, so for the 1mA input of the current, we will have the -0.5V OP-AMP Output. To test this circuit, a current source and an electric multimeter are needed. This test uses the Rigol DP832 Power Supply to provide current from -30mA to +30mA with 1mA resolution and Sanwa CD771 Multimeter to read the voltage output from the I to V converter[9]. The result of the test is shown in Fig. 5.

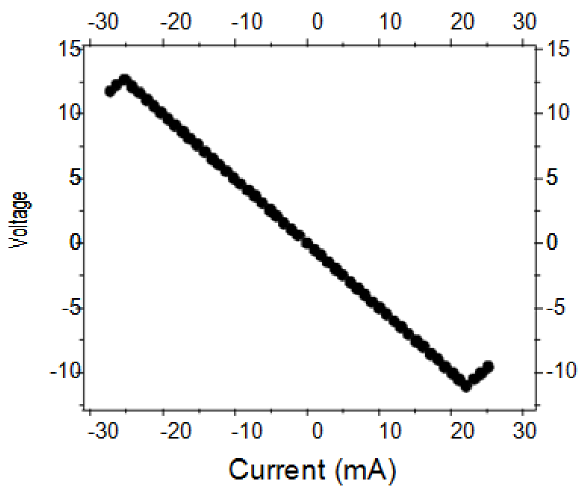

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Fig. 5. I to V Output vs Current Applied.

From the graph above (Fig. 5.), it is evident that the drop voltage occurs when the input current is at -25mA and +22mA. This is due to the limitation of Op amp to supply voltage from Vcc and Vee to output with a range of 3V, which means that the instrument power supply has a voltage of 15V that can be given at the approximate output of 12V [10]. This instrument possesses a bipolar power supply with the value of -15V and +15V, so that theoretically the maximum output of I to V converter is -15V or +15V. Arduino Due can only read the input voltage with 0 – 3.3V range, as applying the voltage below 0V or more than 15V will extremely damage the pins and microprocessor [4]. Attenuator circuit will be of help to reduce the -15 and +15V to 0 – 3.3V. The result of the test is shown in Fig. 6.

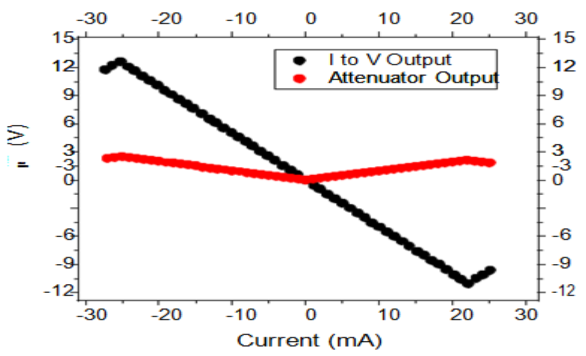

Fig. 6. Attenuator Output and I to V Output.

From the graph above (Fig. 6.), the output of Attenuator has not reached 3V with the 5 times attenuation factor. The negative voltage output from the I to V Converter will also be inverted into positive voltage with the output below of 3V. Consequently, the result shows that Arduino Due will remain safe in carrying out positive and negative current sense within the range of -25mA - +22mA. The last test carried out on the current sense is the reading of the ADC to see the linearity of the current input to the reading of the ADC, as well as the stability possessed by the current sense. Linearity test is done to get the correction factor value and the standard errors that the current sense has, resulting in measurable accuracy. The result of the linearity test for both positive and negative current is shown in Fig.7.

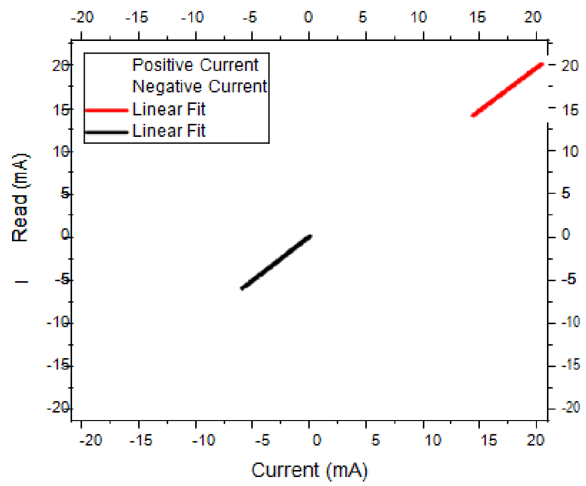

Fig. 7. Linearity test on current sense.

The graph above is a plot of the current read without correction factors. Adjusted R^2 value of the graph reaches 0.99998 where the plot is a linear graph, besides the positive current reading gradient value is 1.001mA with a standard error value of 0.001. As for the negative current the slope value is -1.003mA with a standard error of -0.001. Both slope values will be the correction factor. This results in error value for positive and negative measurement being 0.09% and 0.1% with 99.91% and 99.9% accuracy respectively. The last test is the stability test to see the precision of the current sense by reading the current for about 60 seconds. Figure 8 shows the result of the stability test for both positive and negative current.

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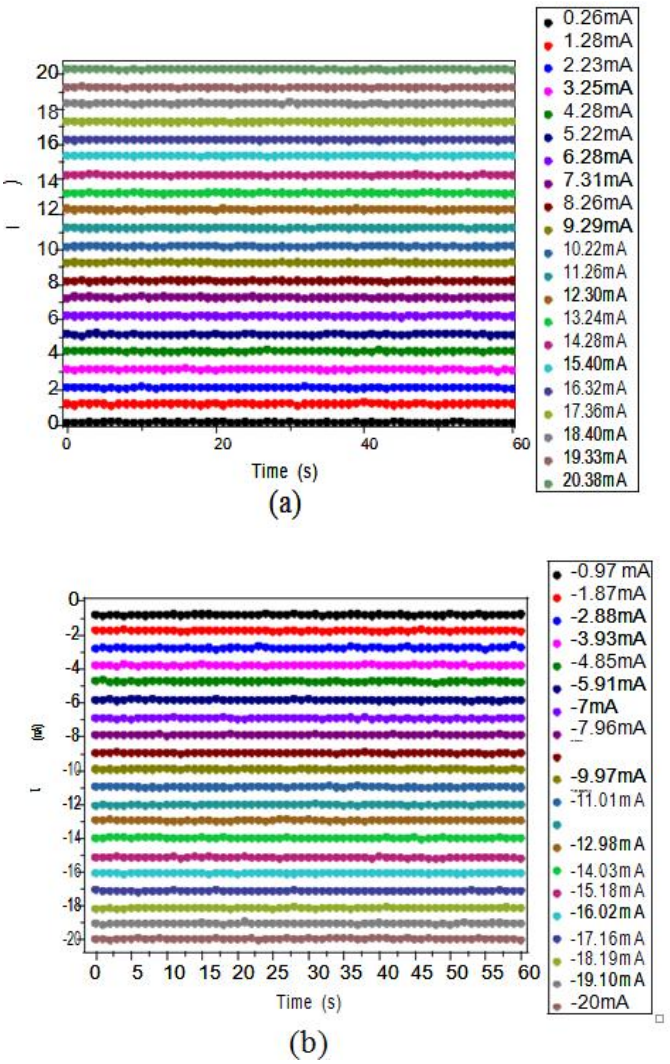

Fig. 8. (a) Current sense stability test for positive current. (b) Current sense stability test for negative current.

Both positive and negative current shows that the reading has an average standard deviation value of 0.02 and an average precision value of 0.06. From the standard deviation and precision values the average error is 1.5% with 98.5% accuracy. From the results above, it can be concluded that the instrument has a high value of precision and accuracy for positive and negative current readings.

III. TESTING THE INSTRUMENT ON ELECTRONIC COMPONENT

The next test was carried out with commonly used and commercially available electronic components to find out the instrument's responses to the linear graph resistors with a value of 500Ω, 5kΩ, and 10kΩ. To find out the instrument's responses to non-linear graphs the test was carried out on 1N4007 diode. To finish, the instrument will be tested to obtain an I-V curve from NPN 2N2369A and PNP S9015 BJTs.

A. 500Ω, 5kΩ and 10kΩ Resistor Test

The first component to be tested is a resistor with a value of 500Ω, 5kΩ and 10kΩ. The purpose of choosing a resistor with this value is because it is still in the measurement range of voltage from 0 – 10V. As discussed earlier, this instrument has limited current sensing ability with a range of -25 mA - +22 mA. The test results for each resistor will be compared and the slope of each graph will be seen in order to find out how well the instrument responds to a linear device. The test uses 2 measurement ports. The two ports are voltage source and current sense port.

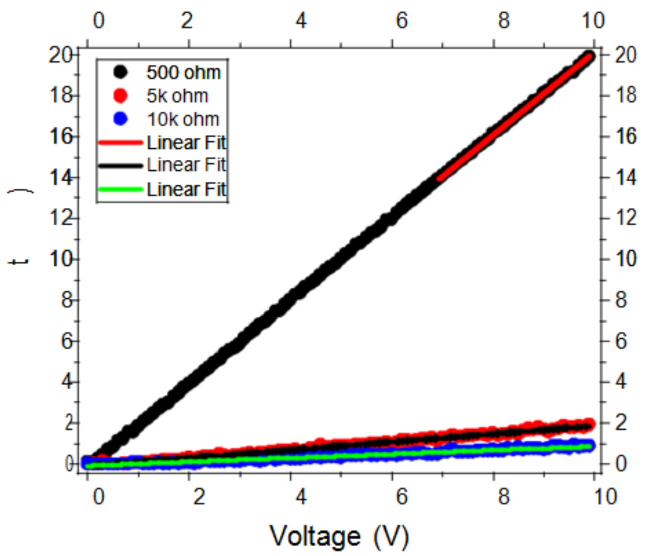

Fig. 9. Current sense test on Resistor with 500Ω, 5kΩ,and 10kΩ variance.

The results of testing the 500 ohm resistors, 5k ohms and 10k ohms above show the values of slope in the order of 2.02627, 0.19709 and 0.09488 (Fig.9.). Theorethically, acquiring the characterization values

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of the three graphs can be done with the basic OHM's law equation [1].

$$I=V/R \quad (3)$$

If we plot in a straight line equation y = x, I (current) will be equal to y, V will be equal to x. Therefore the value of an or slope will be proportional to

$$=1/R \quad (4)$$

The current shown in the graph (Fig. 9.) uses milli amperes units, which means the final result of the characterization value will be multiplied by 1000. Accordingly, the results of the characterization of the three graphs will give R values of 493.5Ω, 5073.8Ω and 10,539.6Ω respectively. The R value obtained by the graph R 500Ω and 5k Ω has a value that is very close to an average error of merely 1.388%, whereas in the graph R 10k Ω the error value reaches 5.396%. The error value arised during the test, where the resistors used in the 500Ω and 5kΩ tests based on the color band each had a tolerance of 1%, yet the tolerance value for testing 10kΩ based on the color band was 5%. This means the three resistor testing graphs are very close to the original with only 0.4% error. In conclusion, it is possible for the instrument to be used to test resistors with a range of -25 mA - +22mA.

B. 1N4007 Diode Test

The next component is 1N4007 diode that is widely available commercially with a maximum current specification of 1A with silicon material, which means the voltage diode threshold reaches saturation at 0.7V [1],[5]. Tests were carried out using a positive voltage source and positive current sensing, which means the P side will be connected to the voltage source and the N side will be connected to the current sense system. Fig. 10 shows the results of after testing the 1N4007 diode.

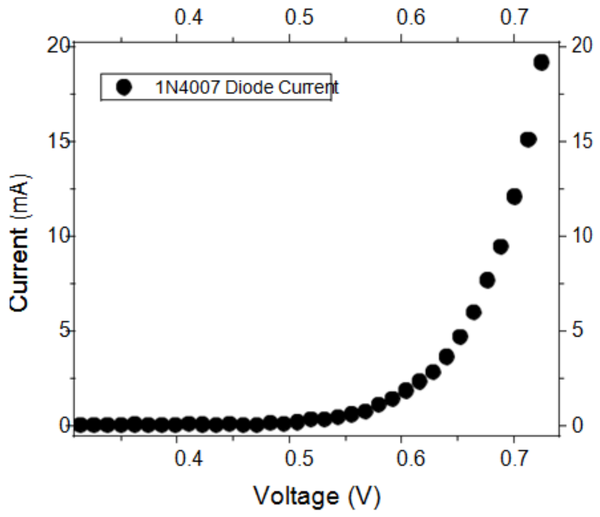

Fig. 10. I-V Curve result for 1N4007 Diode.

From the graph above, the current is measured when the voltage is nearing 0.7 V. According to the datasheet, the current will continue to rise up to 1A if the input voltage is reaching 1.1 V [5]. This cannot be ascertained by the instrument due to the limited measurement up to 22mA. However, the diode test results have shown a diode graph that normally appears and is studied according to the theory and datasheet.

C. BJT Test

There were 2 types of BJT that were tested, the 2N2369A NPN and the 9015 PNP. According to the datasheet, 2N2369A NPN BJT has a maximum collector current value of 200mA, while 9015 PNP BJT has a maximum collector current value of -150mA [11],[12]. BJT has 3 terminal; Base, Collector and Emitter. This means all of the measurement port is used for the measurement.

The first BJT to be tested was the NPN type BJT, 2N2369A. This type of BJT is the part of 2N family BJT. 2N2369A has a casing made of metal, thus enhancing the outside interference protection. As a matter of fact, there are still many more 2N type BJTs such as the 2N2222A, but the type has a high maximum current value of 800mA [13]. 2N2369A has the lowest maximum current value available on the market which is only 200mA [11]. Therefore,

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this type was chosen to take measurements with the instrument.

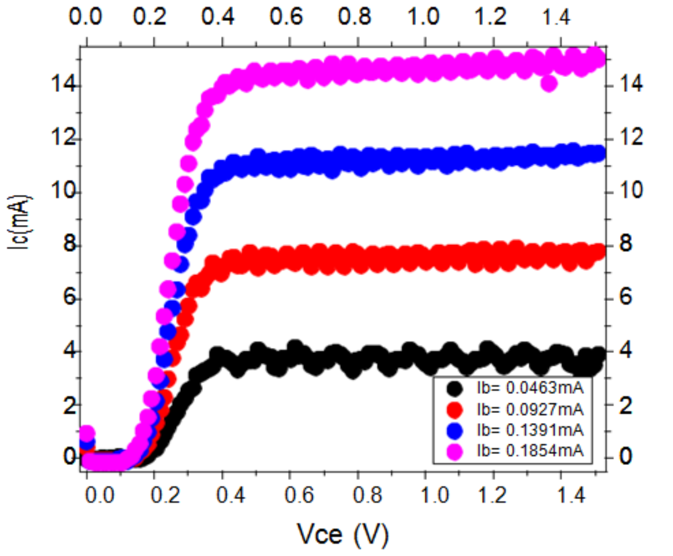

Fig. 21. 2N2369A I-V Curve using the developed instrument.

The graph above (Fig. 11) shows the BJT 2N2369A I-V curve. This graph shows results according to the data sheet where the saturation point is Ic = 10mA and Vce = 0.35 V with an h_{FE} or reinforcement value with a minimum range of 40, typ. 63 and a maximum of 120 [11]. The data obtained at the saturation point is at the value of 10.07mA with the voltage of 0.35V and base current of 0.14 mA. The h_{FE} value is a division between the collector current and the base current. In this graph, the value of h_{FE} is 72. According to the G-3140 graph from the datasheet, the h_{FE} value will change due to the ambient temperature of the BJT. The test was conducted in room temperature of 25°. The G-3140 graph shows that on room temperature with 10mA collector current the h_{FE} value will approximately be 70, which is very close to the result of the mentioned test above[12]. However, as shown in the graph, the current is very unstable and causes saturation points to go up and down. This might be due to the unstable current flowing from the voltage source Vce. As a result, the graph shows a quite large current fluctuations.

The last BJT tested was the PNP 9015 BJT. This type of BJT has h_{FE} value grades that is shown by a letter behind the serial number. This test was conducted on STS9015 with H grade h_{FE} value. According to its datasheet, 9015 has a maximum collector current value of -150mA and h_{FE} value from 100 - 1000 based on its grades[12]. H grade itself has 200 – 600 h_{FE} value. Since this is a PNP BJT, a negative current and a negative voltage are needed at the source.

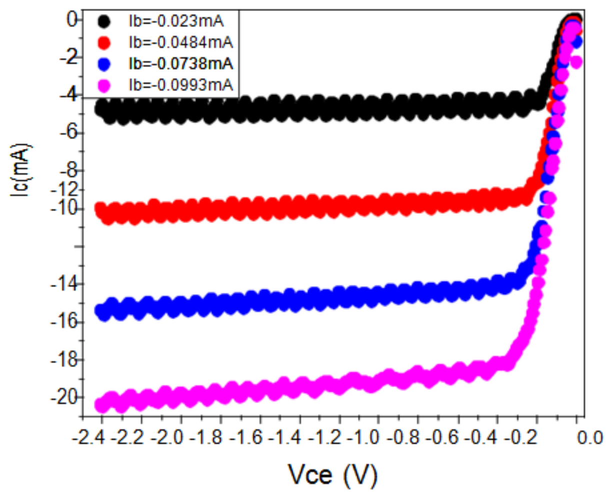

Fig. 32. PNP 9015 I-V Curve using the developed instrument.

Fig. 12 shows an I-V curve for the PNP STS9015 BJT. The current fluctuation is happened due to the unstable voltage and current source. When current with value of 0.023mA, 0.0484mA, 0.0738mA, and 0.0993mA is applied at the base, collector current is saturated with a value of - 4.728mA, -9.91mA, -14.779mA and -19.372mA. Therefore, the h_{FE} value from the results above is 205, 204, 199 and 195. The datasheet from STS9015 gives a value of 200-600 h_{FE} for H grade, while the tested BJT itself is STS9015H. Fig. 4 from the datasheet also shows that for a 25°C ambient temperature and when the V_{CE} is around -1 V and -5V, the h_{FE} value will be approximately 178 to 200[12]. If we take the minimum h_{FE} value from H grade STS9015 that is 200, the error of the test will be around 2.5%, 2%, 0.5% and 2.5% respectively. Consequently, the

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average error of the test will be 1.875%. From the results above, it is confirmed that the developed instrument is able to measure NPN and PNP BJTs with average error value of less than 2% with a range of -25mA – 22mA current measurement.

IV. CONCLUSION

A prototype system for the BJT I-V curve characterization system with an error value of less than 2% has been made and the 98% accuracy of the reading. The system has a controlled voltage source with a range of -9.9 - 9.9V, a controlled current source with a range of -189.9 - 189.9μA, and a current sensor with a range of -25 - +22mA.

The system that has been made has an advantage of being cheap and integrated, making it easier to get graphical characteristics of I-V electronic components. It is expected to be a learning media for courses, practicums, as well as for research and development.

V. ACKNOWLEDGMENT

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