Indonesian Journal of Electrical Engineering and Computer Science
Vol. 34, No. 3, June 2024, pp. 1463~1471
ISSN: 2502-4752, DOI: 10.11591/ijeecs.v34.i3.pp1463-1471

Integrated electronic system for FET biosensor assessment based on current-voltage curve tracing

Achmad Arif Bryantono[1], Leonardo Kamajaya[1], Fitri[1], Sungkono[1], Herwandi[1], Agwin Fahmi Fahanani[2]
[1]Department of Electronics Engineering, Faculty of Electrical Engineering, State Polytechnic of Malang, Malang, Indonesia
[2]Department of Physiology, Faculty of Medicine, Universitas Brawijaya, Malang, Indonesia

Article Info

Article history:

Received Feb 5, 2024
Revised Feb 23, 2024
Accepted Mar 10, 2024

Keywords:

Data acquisition
FET biosensor measurement
Integrated electronic system
I-V curve tracer
Source measure unit

ABSTRACT

Field-effect transistor (FET) biosensors are pivotal in diverse applications, from environmental monitoring to healthcare diagnostics. Current-voltage (I-V) curve tracing is a powerful method for evaluating FET biosensor behavior, enabling comprehensive analysis of their FET biosensor characteristics. Traditional I-V curve tracing methods often require complex and expensive equipment, limiting their accessibility and practicality for routine sensor assessment. This study aims to develop and demonstrate an integrated electronic system for assessing FET biosensors using I-V curve tracing. The integrated electronic system uses readily available components, including microcontrollers, analog circuitry, and user-friendly software. We developed a compact, low-cost device that generates I-V curves for the FET biosensor. The integrated electronic system successfully generated I-V curves for various FET biosensors. The system demonstrated consistent, reliable performance, portability, and ease of use, making it a practical solution for routine sensor assessment. The average error in measurements using bipolar junction transistors (BJT) and metal-oxide-semiconductor field-effect transistors (MOSFETs) results in 2.62%, and measurements at different pH levels have a sensitivity of 21.6 mV/pH and a linearity of 0.9892. This innovation contributes to the advancement of FET biosensor technology. In the future, the developments should focus on ensuring their accuracy and reliability in various sensor fields.

Corresponding Author:

Agwin Fahmi Fahanani
Department of Physiology, Faculty of Medicine, Universitas Brawijaya
East Java, Indonesia
Email: agwinfahmi@ub.ac.id

1. INTRODUCTION

Field-effect transistor (FET) biosensor are indispensable in various applications, from environmental monitoring to medical diagnostics [1]. These sensors' accurate and reliable performance is essential to ensuring the quality and validity of the data collected in these fields. Consequently, the development of methods and tools for the comprehensive evaluation of FET biosensor performance is of paramount importance [2].

The behavior of FET biosensor is intrinsically linked to their FET biosensor characteristics, and characterizing these characteristics is a fundamental aspect of sensor assessment. One powerful technique for this purpose is the acquisition of current-voltage (I-V) curves, which provide insights into sensor performance, including sensitivity, linearity, and response time [3]–[5]. While I-V curve tracing is a valuable method, its practicality has been constrained by the need for expensive, complex equipment. This limitation has spurred the quest for more accessible [6]–[8] and cost-effective alternatives [9], [10].

The research problem addressed in this paper revolves around the inaccessibility and cost barriers associated with traditional I-V curve tracing methods for FET biosensor. Therefore, there exists a pressing need for an integrated electronic system that simplifies the I-V curve tracing process, making it more widely accessible and practical for sensor assessment [11]. The primary objective of this study is to design, develop, and validate an integrated electronic system tailored for FET biosensor assessment using I-V curve tracing. The system is designed to be cost-effective, user-friendly, and portable, addressing the accessibility and practicality issues associated with traditional methods. It aims to provide a valuable resource for researchers and practitioners, enabling efficient and precise characterization of FET biosensor performance.

The proposed solution is an integrated electronic system that combines microcontrollers, analog circuitry, and user-friendly software to facilitate the generation of I-V curves for FET Biosensor. We hypothesize that this system will provide accurate and consistent results in line with those obtained from traditional, more expensive equipment. This paper describes the development of an integrated electronic system based on the I-V curve tracer for the FET biosensor. Therefore, a study of the characteristics of the I-V curve tracer for measuring the bipolar junction transistors (BJT), metal-oxide-semiconductor field-effect transistors (MOSFET), and FET biosensor was carried out. The rest of this paper is structured as follows. Section 2 describes the method used to measure BJT/MOSFET/FET biosensors based on the I-V curve tracer. Section 3 provides the proposed system's characteristics, including electronic specifications and source measure units (SMU). In section 4 tests the proposed system and analyzes the implementation of the FET biosensor. Finally, we conclude the paper in section 5 and discuss future work.

2. METHOD

2.1. I-V curve tracer

The I-V curve tracer plays a crucial role in the characterization and assessment of FET biosensor. This diagnostic tool allows researchers and scientists to gain deep insights into the behavior of these sensors by measuring the relationship between current and voltage across the sensor under various conditions. I-V curve tracing is especially valuable for evaluating sensor performance, determining critical parameters like sensitivity, linearity, and response time, and identifying anomalies or deviations in the FET biosensor behavior [12], [13]. By providing a comprehensive view of how an FET biosensor responds to changes in its environment or target analyte, I-V curve tracers are essential instruments for optimizing sensor design, enhancing accuracy, and ensuring the reliability of data collected in a wide range of applications, from environmental monitoring to healthcare diagnostics.

2.2. Method to obtain the characteristic curves

This paper outlines the methodology for acquiring parameters that characterize the current/voltage relationship I-V curve and pH concentration/threshold voltage (FET biosensor) behaviour. Figure 1 shows block diagram of proposed system and SMU-DUT measurement configuration. The investigations differed in the methodology employed for data collection during the sampling phase. This distinction in data collection methods allowed for a comprehensive analysis of the system's performance under various conditions.

Figure 1(a) shows measurement configuration between SMU and device under test (DUT). Various characterization techniques were employed to produce the subsequent characteristic curves: i) the I_B-V_{CE} characteristic curve is used to measure the performance of a BJT component in the I-V curve tracer of an SMU, ii) the I_D-V_{DS} characteristic curve is used to test the performance of the I-V curve tracer on the SMU for MOSFET components, and iii) this study uses MOSFET components and electrodes with varying pH concentrations to construct a threshold voltage (V_{Th}) to pH concentration characteristic curve. It aims to assess the sensitivity and linearity of the proposed system in utilizing FET biosensor.

2.3. Developments method

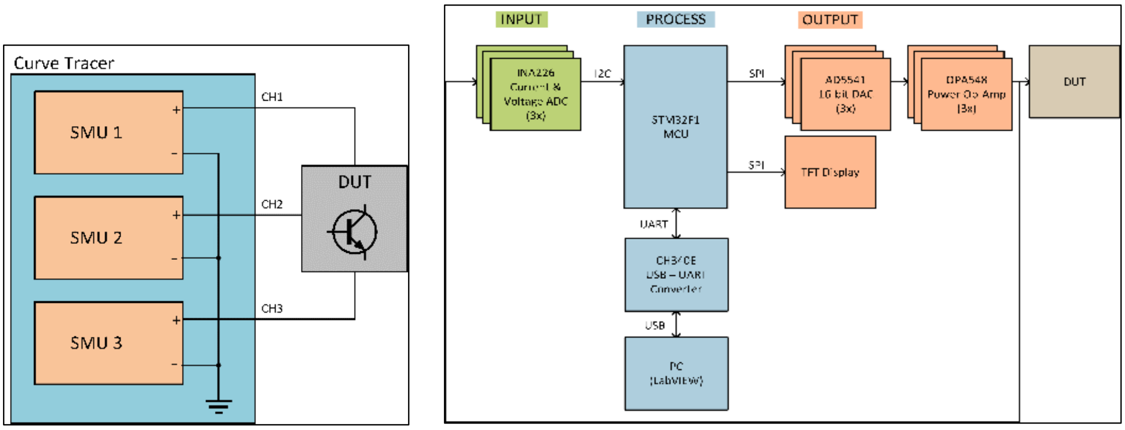
Figure 1(b) describes the system diagram of transistor curve tracer. The input block uses INA226 ADC to measure both the output voltage and current then used as feedback from the control system and data acquisition on the microcontroller using the I2C communication protocol. The process block uses the STM32F1 as the control system to adjust the output voltage and current while acquiring measurement data from INA226. UART is used to communicate with PC that goes through USB-TTL CH340E converter to connect with PC through a universal serial bus (USB) port. On the output block there is a AD5541 DAC to set the output voltage, this signal then amplified by the power op-amp OPA548 [14] that outputs into the DUT controlled by digital data from STM32. The test result graph is displayed with TFT LCD in real time.

Table 1 displays the electrical properties of the proposed system, including a voltage resolution of 0.1, a current resolution of 0.01, and a power resolution of 1. These results demonstrate that the suggested system satisfies the requirements to function as an I-V curve tracer for application in FET biosensors. Furthermore, the system’s accuracy in measuring these electrical properties ensures reliable data collection for analyzing the performance of FET biosensors under various conditions. The system costs a maximum of $228 to integrate the STM32F ($56), BJT/MOSFET ($50), acquisition circuit ($100), and other components (cables, heat sink, and 3D printing materials), making it less expensive than other professional equipment that includes more functionalities than are required.

Table 1. Electrical characteristics of the proposed system

Variable	Range	Resolution	Precision
Voltage	0 – 20V	0.1	0.5%
Current	0 – 1 A	0.01	0.35%
Power	200 mW – 24 W	1	1%

The SMU consists of AD5541 digital to analog converter converter (DAC) to regulates output voltage and current, due to output voltage range from DAC GND (0V) to VREF (3.3V) an amplifier is needed to multiply output voltage range up to 24 volts. Measurement block in this circuit use an analog to DAC that have integrated integrated signal conditioner so that current and voltage measurements can be measured with just an IC and a current sense resistor, I2C communication protocol is used in this ADC [15] so it’s easy to combine multiple blocks into one. Figure 2, specifically Figure 2(a) shows SMU circuit diagram of the system. A SMU is an instrument capable of accurately providing voltage or current while concurrently measuring voltage and/or current [16], [17]. The device integrates the functionalities of a digital multimeter (DMM), power supply, true current source, electronic load, and pulse generator into a single instrument with precise synchronization, packaged in a compact form.



(a) (b)

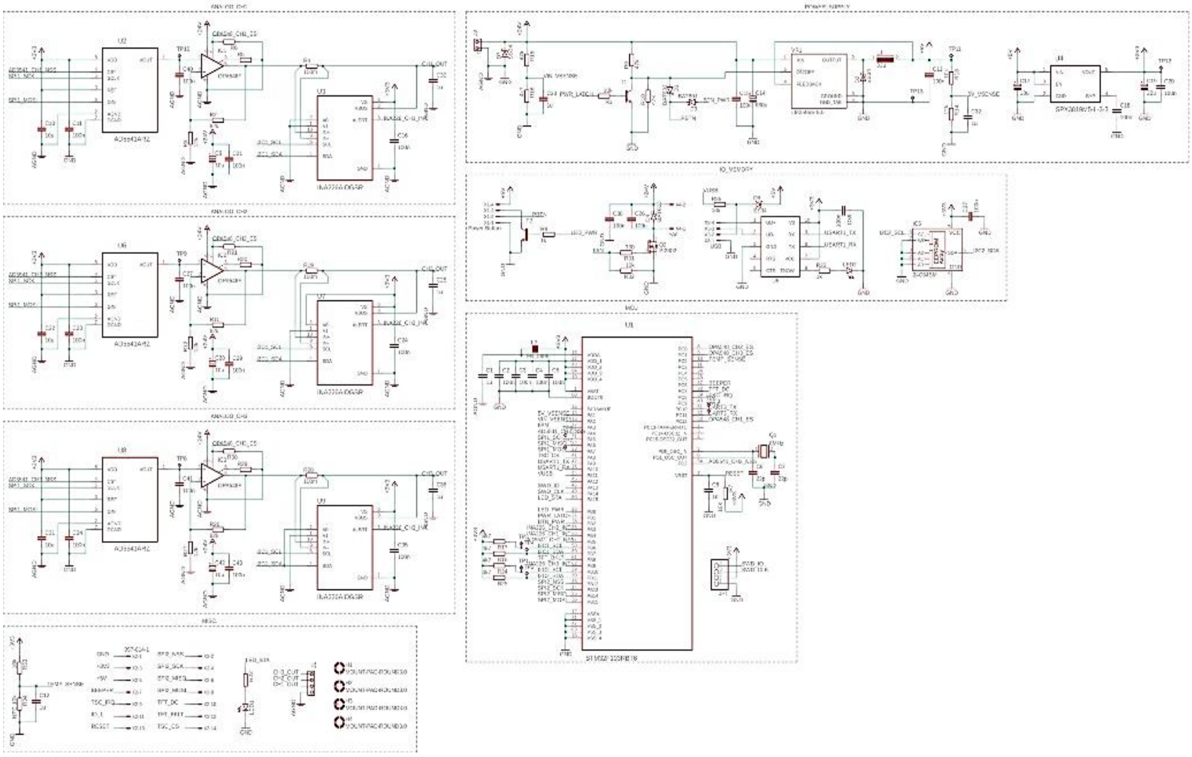
Figure 1. Block diagram of (a) the SMU and DUT measurement configuration and (b) I-V curve tracer

3. RESULTS AND DISCUSSION

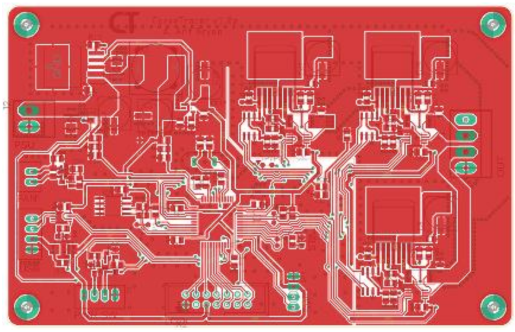
3.1. System hardware contruction

The study creates a small, economical device that produces I-V curves for FET biosensors. Previous research has created I-V curve tracing, but the devices still necessitate complex, costly equipment and restrict the ease of the measurement process. The schematic designs and printed circuit board (PCB) for the electrical circuits of the integrated electronic system prototype were designed. Figure 2 displays the proposed system. The schematic designs and PCBs were meticulously crafted with precision and careful attention to detail. Figure 2(a) demonstrate the entire circuit of proposed system. Furthermore, the offset voltage circuit, which has a constant output of 3.3V, is investigated, as well as the control signal conditioning unit and the BJT/MOSFET. The AD5541 and INA226 are used to focus on the acquisition of voltage and current signals.

It is critical to follow a building technique that includes the installation of a PCB and protective framework, as shown in Figure 2. The printed circuits were built within the available space and power restrictions, resulting in the proposed system circuit shown in Figure 2(a) and the circuit board shown in Figure 2(b). Once the components were obtained, they were integrated and placed in a PLA box, making the equipment portable, as shown in Figure 2(c). Furthermore, the structure electrically isolates the power circuit from the user, as shown in Figure 2(c), which includes the BJT/MOSFET, heat sink, fan, and power supply circuit.



(a)



(b)

(c)

Figure 2. Implementation of the I-V curve tracer system; (a) SMU circuit, (b) top view of the circuit board, and (c) internal system components

3.2. System implementation

Data acquisition with a computer facilitates the processing and analysis of test data results, and LabVIEW is used as an interface and data processor [18]–[20]. This software allows real time monitoring and control of various instruments and sensors, ensuring accurate and efficient data collection. Additionally, LabVIEW provides advanced data analysis tools such as signal processing algorithms and statistical analysis capabilities, enhancing the overall data processing capabilities of the computer system. The LabVIEW-based interface display in Figure 3 showcases the user-friendly and intuitive design, making it easy for researchers to navigate and interpret the collected data. Moreover, LabVIEW offers various customization options, allowing users to tailor the interface to their needs and preferences.

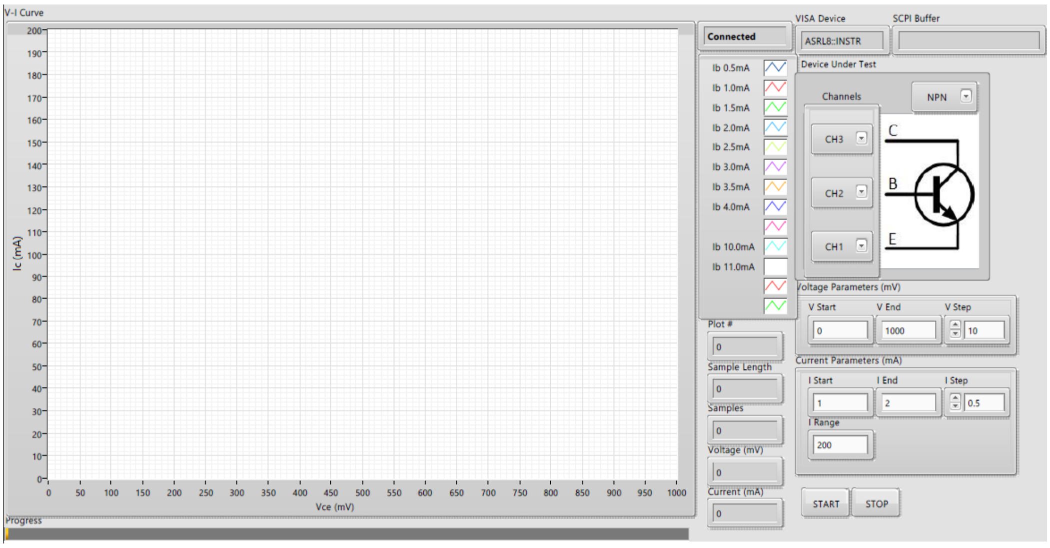


Figure 3. Graphical user interface (GUI) of I-V curve tracer

3.3. Functional and calibration tests

The individual subcircuits were tested using an oscilloscope, multimeter, and the suggested system to assess and confirm the voltage and current outputs of the SMU. Figure 4 depicts the curve tracer's test configuration. Figure 4(a) also includes a block schematic of the curve tracer. Figure 4(b) shows the test circuit for the proposed system's output voltage, while Figure 4(c) shows test circuit for the proposed system's output current. The configuration of the microcontroller was validated to govern a multitude of interconnected devices. The voltage measurements exhibited an average error of 0.01% with a maximum error of 0.05% see in Table 2, whilst the current measurements displayed an average standard deviation and error value of 1.17 and 0.35% see in Table 3, respectively. We found that the maximum error value is 0.52%, which correlates with the change of resistance of R_{Shunt}. The solution proposed in this research is to move the heat source component. Moving the power op-amp to the bottom of the PCB and adding a heatsink tend to lower the temperature, impacting the accuracy.

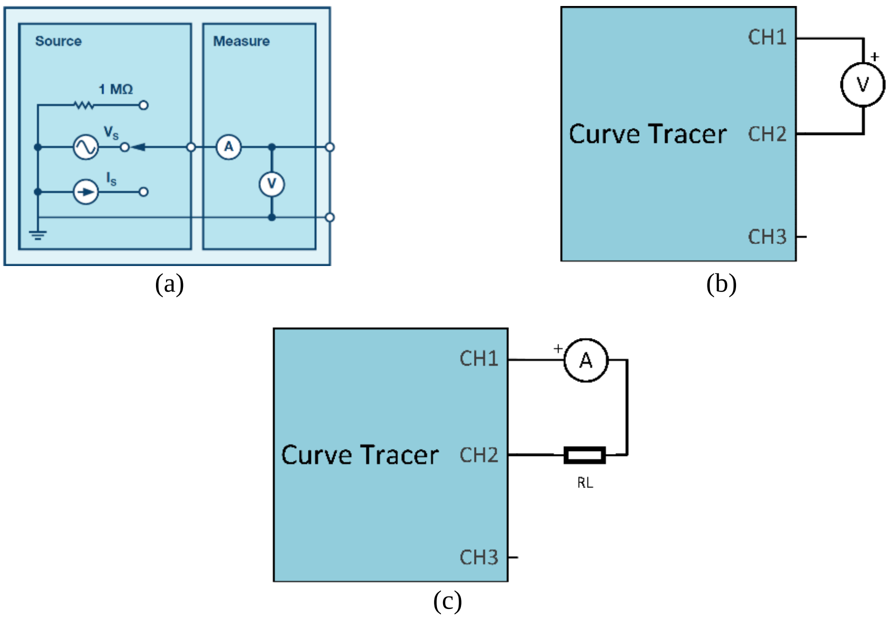


Figure 4. Testing configuration of curve tracer; (a) block diagram of curve tracer [21], (b) test circuit for output voltage, and (c) test circuit for output current

Table 2. SMU voltage measuring test results before and after calibration

No	Setpoint (mV)	Before calibration Measured (mV)	Offset (mV)	After calibration Measured (mV) 1	2	3	Stdev	% Error
1	1000	1001	-1	1000	999	1000	0.58	0.03
2	2000	2000	0	1999	1999	1999	0.00	0.05
3	3000	3002	-2	3000	2999	3001	1.00	0.02
4	4000	4001	-1	4000	3999	4000	0.58	0.01
5	5000	5004	-4	4999	5000	5000	0.58	0.01
6	6000	6004	-4	5999	5999	6000	0.58	0.01
7	7000	7001	-1	7000	6999	7001	1.00	0.01
8	8000	8002	-2	8000	8000	8001	0.58	0.01
9	9000	9003	-3	9001	9000	9001	0.58	0.01
10	10000	10003	-3	10001	10000	10001	0.58	0.01
11	11000	11004	-4	11001	11003	11002	1.00	0.02
12	12000	12003	-3	12001	12002	12000	1.00	0.01
13	13000	13001	-1	13001	13001	13001	0.00	0.01
14	14000	14003	-3	14000	14003	14001	1.53	0.01
15	15000	15001	-1	15001	15002	15000	1.00	0.01
16	16000	16003	-3	15999	16002	16000	1.53	0.01
17	17000	17004	-4	17000	17003	17002	1.53	0.01
18	18000	18002	-2	18000	18002	18001	1.00	0.01
19	19000	19002	-2	19001	19002	19001	0.58	0.01
20	20000	20004	-4	20001	20002	20001	0.58	0.01
Average			-2.4				0.79	0.01

Table 3. SMU current measuring test results before and after calibration

No	Setpoint (mA)	Before calibration Measured (mA)	Offset (mA)	After calibration Measured (mA) 1	2	3	Stdev	% Error
1	100.0	100.1	-0.1	99.7	99.7	99.6	0.06	0.33
2	200.0	199.7	0.3	199.7	199.3	199.1	0.30	0.32
3	300.0	299.2	0.8	299.4	299.1	298.7	0.35	0.31
4	400.0	399.7	0.3	399.0	398.5	397.9	0.82	0.32
5	500.0	500.1	-0.1	499.3	498.2	497.7	0.82	0.32
6	600.0	598.8	1.2	599.0	597.4	597.0	1.06	0.37
7	700.0	699.7	0.3	701.7	696.8	695.9	3.12	0.43
8	800.0	799.7	0.3	797.2	794.5	795.7	1.35	0.52
9	900.0	899.3	0.7	901.9	896.4	896.9	3.04	0.32
10	1000.0	994.5	5.5	997.2	998.7	999.2	1.04	0.16
Average			0.92				1.17	0.35

3.4. Field tests using BJT and MOSFET as DUT

Table 4 displays the aggregated average values calculations for BJTs and MOSFETs. The collective findings reveal an average discrepancy of 2.62%. Measurement errors in BJT and MOSFET measurements utilizing SMU encompass: Self-heating occurs when a device experiences an increase in temperature due to the passage of a high current, resulting in potential measurement inaccuracies [22]. This is especially applicable to high-power semiconductors. Parasitic elements, such as stray capacitance and inductance, can impact measurement accuracy [23]. This holds particularly true for measurements conducted at high frequencies. Switching errors can arise when measuring capacitance through a switching matrix, attributable to the time taken for the matrix to switch [24].

The use of a high-speed SMU can help mitigate this issue. Contact resistance refers to the resistance that arises at the point of contact between the device being tested and the measurement probes. This resistance has the potential to impact the accuracy of measurements [25]. To minimize this issue, it is advisable to utilize low-resistance probes and ensure optimal contact between the probes and the device. Instrument noise can impact measurement accuracy. This can be reduced by utilizing instruments that have low levels of noise. Calibration errors can result in inaccurate measurements [26]. Regular calibration and maintenance of the instrument are crucial to ensure its proper functioning. This study examines the detailed measurement properties of BJT and MOSFET components concerning self-heating and temperature rise. Additionally, comprehensive research is required to verify the impact of these parameters on measurement precision, particularly in utilizing low-resistance probes and consistent calibration to reduce inaccurate measurements.

Table 4. The average error for twelve components using the proposed system

Type	DUT	Error (%)	Type	DUT	Error (%)
BJT	TIP41	1.60	FET	IRF530	3.55
BJT	BD139	0.27	FET	IRF540	5.56
BJT	C828	2.24	FET	IRF630	1.50
BJT	TIP42	0.48	FET	IRF9530	3.89
BJT	BD140	1.47	FET	IRF9540	6.66
BJT	A564	1.53	FET	SFS9630	2.71
Average					2.62

3.5. Field tests using FET biosensor

FET biosensors work on the idea that the charge distribution at the FET-solution interface changes as target analytes bind or interact with the sensing surface. The pH of the solution impacts the concentration of hydrogen ions (H+), which influences the electrical characteristics of the FET. This section details the testing of the suggested I-V curve tracer-based system in the field of FET biosensors. This test was carried out utilizing the circuit depicted in Figure 5. The circuit includes an electrode attached to the NMOS gate terminal, a reference electrode made of Ag/AgCl, and a pH solution that is adjusted. The threshold voltage was determined in this test using the ID-VG characteristic curve.

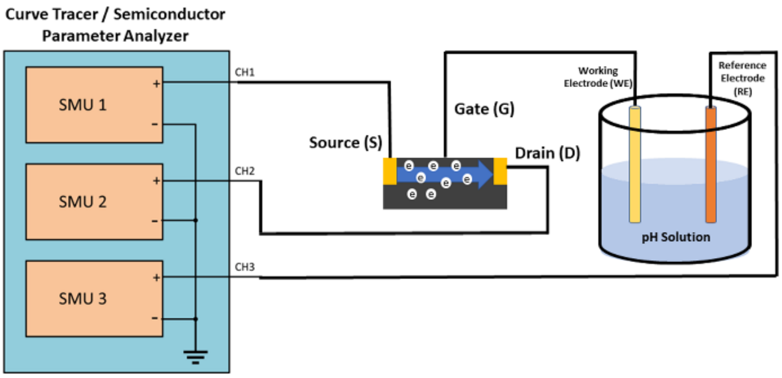
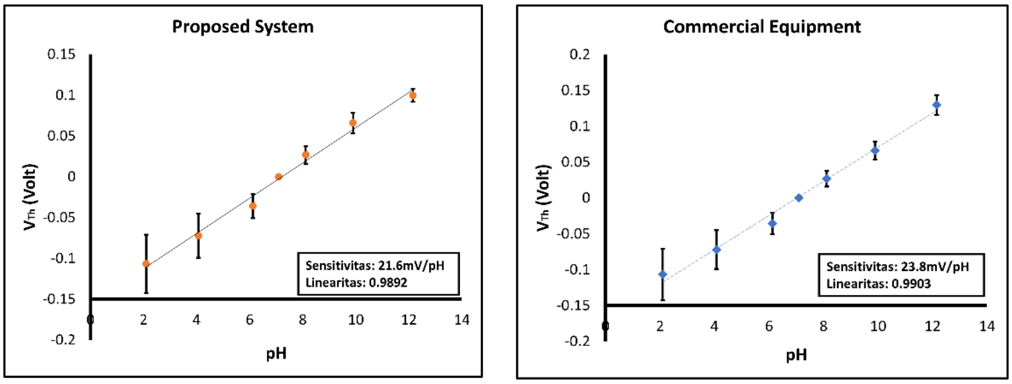


Figure 5. Block diagram of pH concentration measurement

Figure 6 shows the I-V characteristics curve of the FET biosensor implementation for the proposed system see in Figure 6(a) and commercial equipment see in Figure 6(b). According to the measurement results, the proposed system has a sensitivity of 21.6 mV/pH and a linearity of 0.9892. For commercial equipment, it has a sensitivity of 23.8 mV/pH and a linearity of 0.9903. Our study indicates that the sensitivity and linearity values of the suggested system are slightly lower than those of commercial equipment when measuring with an FET biosensor. However, our study demonstrates that the proposed system shows favourable results due to its reduced cost and simplicity compared to commercial equipment. Future studies may explore the sensitivity and linearity of the proposed system with feasible ways of producing pH measurements in specific applications.



(a) (b)

Figure 6. The I-V characteristics curve of (a) the proposed system and (b) the commercial equipment

4. CONCLUSION

This study was to develop an integrated electronic system capable of generating I-V curves for FET Biosensor sensors and making this assessment method more accessible. The system effectively met this objective, offering a low-cost, user-friendly solution for routine sensor evaluation. The results of the testing and evaluation of the integrated electronic system were consistent and reliable. It successfully generated I-V curves for various FET biosensor sensors, providing valuable insights into their FET biosensor behavior. The average error in measurements using BJT and MOSFET results in 2.62%, and measurements at different pH levels have a sensitivity of 21.6 mV/pH and a linearity of 0.9892. These results agreed with those obtained using traditional, more expensive equipment. The system's portability and ease of use make it a practical tool for researchers and practitioners, ensuring the accuracy and reliability of FET biosensor sensor data. The future work from this research is about enhancing system capabilities, real-world applications, user interface and software, data analysis, and integration with other sensor types. Future work will contribute to the ongoing development of this system and its broader applicability in sensor evaluation and analysis.

REFERENCES

[1] D. Sadighbayan, M. Hasanzadeh, and E. Ghafar-Zadeh, "Biosensing based on field-effect transistors (FET): recent progress and challenges," *TrAC Trends in Analytical Chemistry*, vol. 133, p. 116067, 2020, doi: 10.1016/j.trac.2020.116067.

[2] L. Chao *et al.*, "Recent advances in field effect transistor biosensor technology for cancer detection: a mini review," *Journal of Physics D: Applied Physics*, vol. 55, no. 15, p. 153001, Apr. 2022, doi: 10.1088/1361-6463/ac3f5a.

[3] A. Das, "An easy-to-fabricate source measure unit for real-time DC and time-varying characterization of multi-terminal semiconductor devices," *Engineering Research Express*, vol. 3, no. 1, p. 015003, Mar. 2021, doi: 10.1088/2631-8695/abd687.

[4] M. J. Deen and F. Pascal, "Electrical characterization of semiconductor materials and devices," *Journal of Materials Science: Materials in Electronics*, vol. 17, no. 8, pp. 549–575, 2006, doi: 10.1007/978-3-319-48933-920.

[5] E. Buchicchio, A. De Angelis, F. Santoni, and P. Carbone, "EasyEIS: a software tool to perform electrochemical impedance spectroscopy using a source measure unit," *SoftwareX*, vol. 18, p. 101075, Jun. 2022, doi: 10.1016/j.softx.2022.101075.

[6] L. J. Bradley and N. G. Wright, "Electrical Measurements and parameter extraction of commercial devices through an automated MATLAB-Arduino system," *IEEE Transactions on Instrumentation and Measurement*, vol. 70, 2021, doi: 10.1109/TIM.2021.3104041.

[7] L. Jones, M. Mitkova, and N. Rafla, "Low-cost test and characterization platform for memristors," in *2021 IEEE Workshop on Microelectronics and Electron Devices (WMED)*, Apr. 2021, pp. 1–4, doi: 10.1109/WMED49473.2021.9425110.

[8] D. Nichols, "Arduino-based data acquisition into Excel, LabVIEW, and MATLAB," *The Physics Teacher*, vol. 55, no. 4, pp. 226–227, 2017, doi: 10.1119/1.4978720.

[9] E. Moreno-Garcia, "Curve tracer with a personal computer and LabView," in *14th International Conference on Electronics, Communications and Computers, 2004. CONIELECOMP 2004*, 2004, pp. 202–207, doi: 10.1109/ICECC.2004.1269573.

[10] N. Prokop, L. Greer, M. Krasowski, J. Flatico, and D. Spina, "A miniature microcontroller curve tracing circuit for space flight testing transistors," *Review of Scientific Instruments*, vol. 86, no. 2, Feb. 2015, doi: 10.1063/1.4908163.

[11] Y. Chen, H. R. Kim, Y. J. Ahn, and J. B. Kim, "Characteristic curves of the photodiode and phototransistor with Arduino," *Physics Education*, vol. 58, no. 5, p. 055018, Sep. 2023, doi: 10.1088/1361-6552/ace8e8.

[12] Y. Zhu and W. Xiao, "A comprehensive review of topologies for photovoltaic I–V curve tracer," *Solar Energy*, vol. 196, pp. 346–357, Jan. 2020, doi: 10.1016/j.solener.2019.12.020.

[13] P. Papageorgas, D. Piromalis, T. Valavanis, S. Kambasis, T. Iliopoulou, and G. Vokas, "A low-cost and fast PV I-V curve tracer based on an open source platform with M2M communication capabilities for preventive monitoring," *Energy Procedia*, vol. 74, pp. 423–438, Aug. 2015, doi: 10.1016/j.egypro.2015.07.641.

[14] W. Jung, *Op Amp Applications Handbook*. Elsevier, 2005.

[15] P. Parandiy, N. Pelypets, and B. Turko, "Microprocessor system as analyzing complex of gas and vapour sensors," in *2021 IEEE 12th International Conference on Electronics and Information Technologies (ELIT)*, 2021, pp. 41–45,.

[16] R. Ortega, "New source measure unit architecture for control loop configurability," in *2012 IEEE AUTOTESTCON Proceedings*, Sep. 2012, pp. 157–160, doi: 10.1109/AUTEST.2012.6334556.

[17] P. Stoliar, "Source-measuring unit for characterizing resistive switching devices," *Review of Scientific Instruments*, vol. 91, no. 6, Jun. 2020, doi: 10.1063/1.5140812.

[18] G. Ellis, *Control system design guide: using your computer to understand and diagnose feedback controllers*. Butterworth-Heinemann, 2012.

[19] B. A. Balaji, S. Sasikumar, and K. Ramesh, "SCPI based integrated test and measurement environment using LabVIEW," *IOP Conference Series: Materials Science and Engineering*, vol. 1045, no. 1, 2021, doi: 10.1088/1757-899X/1045/1/012036.

[20] J. Kodosky, "LabVIEW," *Proceedings of the ACM on Programming Languages*, vol. 4, Jun. 2020, doi: 10.1145/3386328.

[21] D. Mercer and A. Miclaus, "ADALM1000 SMU Training," Analog Devices, 2018. https://www.analog.com/media/en/analog-dialogue/studentzone/studentzone-12-2018.pdf (accessed Jan. 10, 2024).

[22] C. A. B. Mori, P. G. D. Agopian, and J. A. Martino, "New approach for removing the self-heating from MOSFET current using only DC characteristics," in *2018 IEEE SOI-3D-Subthreshold Microelectronics Technology Unified Conference, S3S 2018*, Oct. 2018, pp. 1–3, doi: 10.1109/S3S.2018.8640180.

[23] P. Yu, L. Sun, J. Cheng, and J. Gao, "Sensitivity analysis and uncertainty estimation for nanoscale MOSFET," *International Journal of Numerical Modelling: Electronic Networks, Devices and Fields*, vol. 31, no. 5, 2018, doi: 10.1002/jnm.2346.

[24] H. Sakairi, T. Yanagi, H. Otake, N. Kuroda, and H. Tanigawa, "Measurement methodology for accurate modeling of SiC MOSFET switching behavior over wide voltage and current ranges," *IEEE Transactions on Power Electronics*, vol. 33, no. 9, pp. 7314–7325, Sep. 2018, doi: 10.1109/TPEL.2017.2764632.

[24] S. B. Mitta *et al.*, "Electrical characterization of 2D materials-based field-effect transistors," *2D Materials*, vol. 8, no. 1, p. 012002, Jan. 2021, doi: 10.1088/2053-1583/abc187.

[26] E. T. Nejad, F. A. Mohammadi, and E. Astvatsatryan, "Development of a device characterization curve tracer based on transient thermal measurement," in *2011 24th Canadian Conference on Electrical and Computer Engineering(CCECE)*, May 2011, pp. 001198–001201, doi: 10.1109/CCECE.2011.6030652.

BIOGRAPHIES OF AUTHORS

Achmad Arif Bryantono received S.Tr.T. (Bachelor of Engineering) degree in electronics engineering from State Polytechnic of Malang, Indonesia. His research interests include measurement technology, data acquisition, and robotics. He can be contacted at email: a.arifbryan@gmail.com.

Leonardo Kamajaya is a lecturer in Electronic Engineering Study Program at State Polytechnic of Malang. He received a bachelor's degree in Electronic Engineering at Politeknik Elektronika Negeri Surabaya and a master's degree in Electrical Engineering at Chang Gung University. His research interests include a biosensor, electronics systems, electronics projects based on the internet of things (IoT), and renewable energy. He can be contacted at email: leonardo42@polinema.ac.id.

Fitri is a lecturer in Electronic Engineering Study Program at State Polytechnic of Malang. She received bachelor's and master's degrees at Brawijaya University. Her research interests include a sensor, renewable energy, and embedded system. She can be contacted by email: fitri@polinema.ac.id.

Sungkono is a lecturer in Electronic Engineering Study Program at State Polytechnic of Malang. He received bachelor's and master's degrees at Brawijaya University. His research interests include a electronics systems, industrial control, renewable energy. He can be contacted at email: sungkono@polinema.ac.id.

Herwandi is a lecturer in Electronic Engineering Study Program at State Polytechnic of Malang. He received bachelor's and master's degrees at Brawijaya University. His research interests include an electronics system, industrial control, renewable energy. He can be contacted at email: herwandi@polinema.ac.id.

Agwin Fahmi Fahanani is a biomedical engineering researcher and lecturer in Medical Bachelor in Faculty of Medicine, Universitas Brawijaya, Malang, Indonesia. He received a bachelor's degree in electrical engineering at Universitas Brawijaya and a master's degree in electrical engineering (biomedical engineering consentration) at Institut Teknologi Bandung. His research interests include medical image processing, biosensor, and medical devices. He can be contacted at email: agwinfahmi@ub.ac.id.