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NANOX

Testing Validity of Chips
Test System for Validation of Field Emission Chips
used by NANOX VISION

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Abstract

NANOX VISION develops new technology for X-ray imaging based on field emission chips. These chips are used as the electron source in digital X-ray tubes. One of the essential parameters that can predict the reliability and lifetime of the chip is the DC resistance between the gate and the cathode at different voltage/current levels (I/V).

Based on measurements of NANOX, we have the range of resistance for valid chips. So, we can verify that the resistance of the chip under test is within the acceptable range for valid chips.

The project aims to design and build a specific prototype tester for those chips. The system we are developing will utilize the chip's unique design so that the testing process will include additional measurements in a simple and efficient operation.

The main system parts are:

- A measuring circuit based on a precise voltage-controlled current source.
- A program that controls the entire testing process through an Arduino microcontroller, processes the data and determines the validity of the chip.

Introduction

NANOX's Technology

Nanox is a company specializing in manufacturing medical imaging systems.[i] Their medical imaging system incorporates an innovative digital X-ray source.

The X-ray tube operates by accelerating an electron beam from a negatively charged source (cathode) to a positively charged target (anode). When the electrons hit the anode, they release energy in the form of heat and X-rays. The cathode is a crucial component responsible for providing the electrons used in generating X-rays.

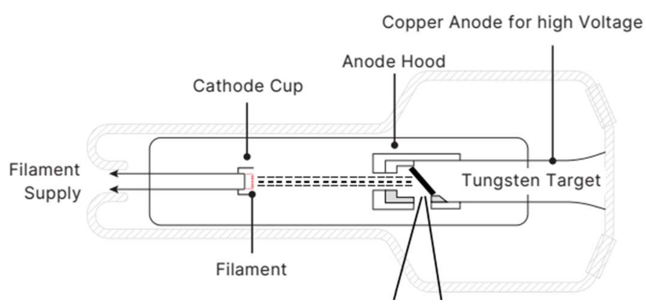

FIGURE 1 BASIC X-RAY TUBE

Traditional cathodes rely on thermionic emission, a process like how an Edison light bulb emits light. In X-ray tubes with thermionic cathodes, a filament is electrically heated to incandescence to emit free electrons. The heating procedure consumes a significant amount of both energy and resources.

Nanox uses a Cold Cathode technology,[ii] where the cathode is not electrically heated by a filament. Instead, electrons are extracted from the metal through an external electric field.

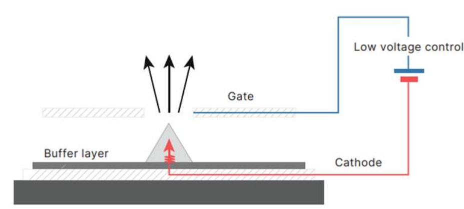

FIGURE 2 NANO-SPINDT COLD CATHODE CHIP TECHNOLOGY

Their standard design features a silicon chip measuring one square centimeter with numerous nanometre-sized gates and conical tips. This design enables a high electric field to be induced at the nanoscale gap between the emitter cone and the gate hole. This high electric field effectively extracts electrons from the emitter, even at a low applied voltage of 50 volts at the gate.

Importance of I-V Characteristics

During the manufacturing process, the company conducts comprehensive tests and precise measurements on the chip to assess its reliability and lifetime. An essential factor in this assessment is the DC resistance between the Gate and Cathode through the silicon. Notably, the resistance of the chip deviates from Ohm's law and exhibits voltage-dependent variability. As a result, to determine the I-V characteristics of the chip, measurements must be taken across various voltage/current levels.

Current Test Process

I/V measurements can be conducted using commercially available test equipment. Nanox presently utilizes the Keithley source meter unit (SMU) for this purpose. However, this approach presents drawbacks, including:

- High acquisition expenses (each unit costs more than $ 10,000).
- Demanding skilled personnel for operation.
- Unsuitable for large-scale production.

Project Goal and Main Requirements

The project aims to create a test system capable of measuring the I-V characteristic of Nanox's field emission chip across a range of applied voltages. The system should be designed to be user-friendly and automated. Workers can easily place chips in their designated positions and the system will indicate whether they are defective or not.

The main requirement for our project is the construction of a prototype for a precise and accurate automatic measurement device to recognize damaged chips, which:

- Device cost should not exceed $100.
- User-friendly and easy-to-operate design.
- Achieve DC resistance accuracy of 90%.
- Compatibility with large-scale production.
- Generation of I-V characteristics as part of its output for research purposes.

Methods

Source Measurement

The source measurement method is a well-established technique employed in measuring resistivity and other electrical properties of materials.[iii] It involves the application of a known current to a sample material and simultaneously measuring the resulting voltage.

In this method, a precise current source is used to generate a controlled electrical current through the sample. The voltage across the sample is then measured using a sensitive voltmeter.

One key advantage of this method is its ability to provide accurate measurements across a wide range of resistances, from low to high values. Additionally, the method allows for precise control of the applied current, ensuring consistent and repeatable measurements.

System Architecture

The system's high-level design, depicted in the figure below (Figure 3), can be described as follows:

- A Python script creates a specific measurement procedure for the Arduino microcontroller.
- The Arduino interfaces with a Digital-to-Analog Converter (DAC) and manages a circuit-connected switching resistors.
- By selecting appropriate values for the shunt resistance and configuring the voltage input, a predetermined current is established, which flows through the device under test (DUT).
- By employing an Instrumentation Amplifier along with its Analog-to-Digital Converter (ADC), the Arduino measures the voltage drop occurring across the DUT.

- The Python program receives the measured data from the Arduino and stores this data for further analysis.

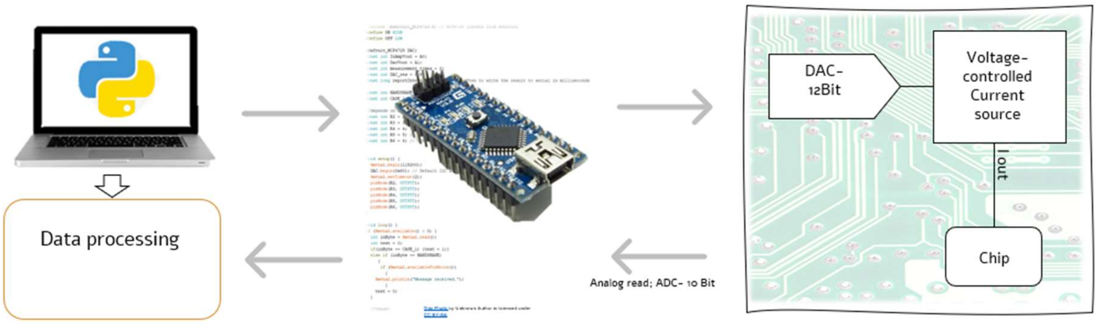

FIGURE 3 DEVICE FLOW OF OPERATION

Board Design

The main task of the project involves the design and development of a source measurement circuit, with the central component being a Voltage to Current converter.[iv] A voltage-to-current (V-I) converter accepts as an input a voltage V_{in} and gives an output current of a certain value. In general, the relationship between the input voltage and the output current is:

$$I_{out} = SV_{in}$$

Where S is the sensitivity or gain of the V-I converter.

We designed (as Figure 5 below shows) a voltage-to-current converter using an Op-Amp and a transistor.

This configuration employs the Op-Amp in a feedback amplifier setup.

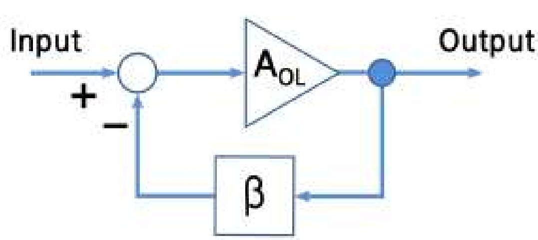

FIGURE 4 IDEAL NEGATIVE-FEEDBACK AMPLIFIER

The transfer function of this stage is given by: $\frac{V_{out}}{V_{in}} = \frac{A_v}{1+A_v\beta}$, where A_v represents the open-loop gain (ideally $A_v \to \infty$) and β is the feedback factor (in our design $\beta = 1$), consequentially $\frac{V_{out}}{V_{in}}$ is approximately equal to 1. The Op-Amp enforces equality between its positive and negative inputs, making the voltage at the negative input of the Op-Amp is equal to V_{in}. The current through the load resistor, RL, (the DUT in our system) is equal to $\frac{V_{in}}{R}$. We put a transistor at the output of the Op-Amp since the transistor is a high current gain stage.

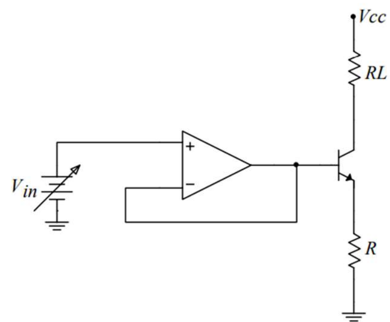

FIGURE 5 CURRENT TO VOLTAGE CONVERTER

The resistance of Nanox's chip depends on the manufacturing process, leading to variations from one chip to another. Additionally, as previously noted, this resistance changes in response to the applied voltage. It is essential for the output current of the Voltage-to-Current (V-I) converter to span a broad range, covering a range of values from $100\ nA$ (nanoamp) to $10\ mA$ (milliamp).

To achieve this versatile capability, we have introduced a resistor array (in place of a single resistor R) that can be selectively controlled through transistor-driven switching mechanisms. By adopting this arrangement, the system acquires the ability to dynamically adjust the resistor's value, thereby finely regulating the resulting output current. The additional resistance added by the transistors is low, with a maximum of 5.3Ω, making it negligible when compared to the resistors. It is also possible to account for this resistance in the software.

In conclusion, this configuration provides the system with two degrees of freedom to precisely determine the current that flowing through the chip.

The Device Under Test (DUT) operates without a ground short on its two terminals, resulting in a floating voltage drop. To measure this voltage, a reading across both terminals is necessary. However, a significant common-mode interference is present. To address this, each terminal is linked to an instrumental amplifier input (with high CMR). The resultant output signifies the voltage difference between the DUT's two terminals.

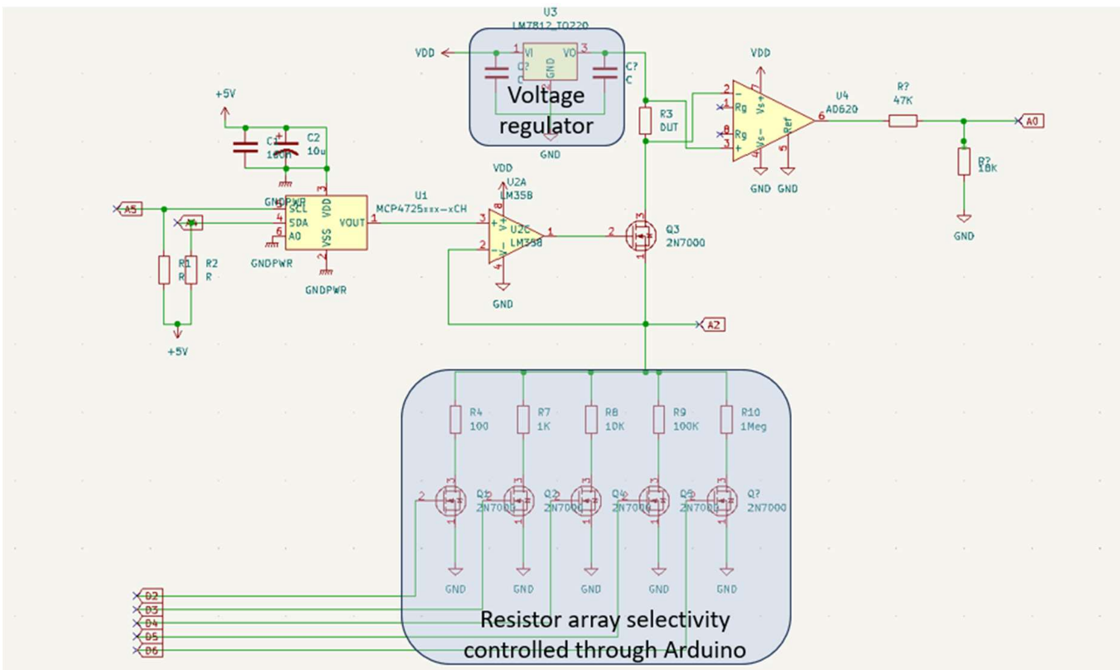

FIGURE 6 THE SCHEME OF THE CIRCUIT

Control and Management

To manage and oversee the entire process, we used a Python and Arduino program. You can access the code we wrote for the project via the following GitHub link[v].

Python Script

The Python script is designed to manage and control the complete system's operations. It first validates communication with the microcontroller and then prompts the user to select an operational mode from three available options. These modes include a general sweep across predefined current values, a sweep across a specified range of current values, and a mode for specifying a particular current through the chip.

Once the user specifies the desired operating mode, the Python script sends a command to the microcontroller to initiate the testing program. All measurements obtained by the microcontroller are saved within the software. Upon completion of the test process, the program will suggest the user to save all the collected data into a CSV file. Additionally, it inquires whether the user wishes to continue with further testing on the chip.

Microcontroller

To manage the input and output of our electrical board we used an Arduino. The Arduino microcontroller is equipped with sets of digital and analog input/output (I/O) pins and is convenient and inexpensive. The Arduino employs a serial communication to get from the Python program the testing mode and additional data depending on the chosen mode of operation.

The operational flow of the Arduino involves two distinct loops, one to iterate over resistors and the other to cycle through the DAC values. The determination of the precise current passing through the DUT deepens upon the selected resistor and the configured DAC voltage. For each current iteration, the Arduino employs its internal Analog-to-Digital Converter (ADC) to measure the voltage drop across the DUT, offering a resolution of 10 bits across a range of 0 to 5 volts.

To ensure accuracy in our measurements, we conduct five repetitions of each reading, averaging the results, with a half-second delay before each measurement to allow the transistor to stabilize. Each measurement, alongside the associated DAC voltage and resistor data, is transmitted to the Python script via serial communication.

Materials

Arduino Nano

Arduino Nano is a microcontroller board based on the ATmega328P (manufactured by microchip). The board runs at a clock speed of 16 MHz, and can provide up to 5V, has 48KB CPU Flash memory. The board includes a 10-bit Analog-to-Digital Converter (ADC) that measures the value of analog signals. Arduino Nano serves as the central processing unit, orchestrating the flow of information and commands between various components.

FIGURE 7 ARDUINO NANO

MCP4725: Digital-to-Analog Converter (DAC)

The MCP4725 device is designed to convert 12-bit digital values into analog voltages. [vi] The output voltage it produces is rail-to-rail and proportional to the power pin, allowing accurate control over the output voltage levels. With its integration of the I2C communication protocol[vii], the MCP4725 ensures precision and efficiency in transmitting data.

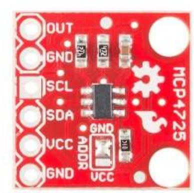

FIGURE 8 MCP4725 DAC

LM358: Operational Amplifier

LM358 is a dual op-amp IC integrated with two op-amps powered by a common power supply.[viii] The differential input voltage range can be equal to that of the power supply voltage. The default input offset voltage is very low which is of magnitude 2mV. The typical supply current is 500uA independent of the supply voltage range and a maximum current of 700uA.

AD620: Instrumentation Amplifier

The AD620 is an Instrumentation amplifier that offers high Common-Mode Rejection (CMR), which is a measure of the change in output voltage when both inputs are changed by equal amounts.[ix]

LM7812: 12 Voltage Regulator

LM7812 is a linear voltage regulator integrated circuit (IC) that provides a constant fixed output voltage regardless of a change in the load or input voltage.[x] A linear voltage regulator works by automatically adjusting the resistance via a feedback loop, accounting for changes in both load and input, all while keeping the output voltage constant.

In the circuit, one DUT side connects to the circuit's power supply, shared with the instrumental amplifier. This terminal feeds into an InAmp input, yet the InAmp's input range must stay below $VCC - 1.6V$. We address this by implementing a voltage regulator to decrease the voltage for this side.

2N7000 Transistor

The 2N7000 transistor shows extremely high packing density for low onresistance, rugged avalanche characteristics, and less critical alignment steps. It has on resistance up to 5.3Ω, and can drive up to 75mA[xi].

PCB

While working on the project, we developed a prototype to evaluate design performance. Upon confirming that the board's behaviour met system requirements, our supervisor edited the schematic into a PCB layout.

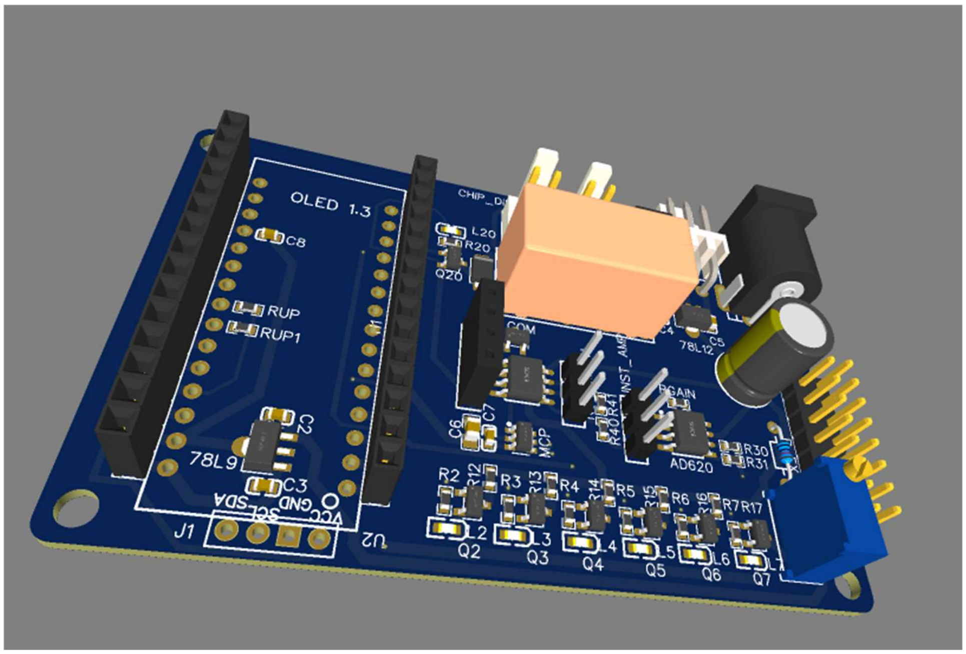

FIGURE 9 THE PCB DESIGN

Results

In our project, we successfully developed a automated user-friendly system. Anyone, even without technical expertise, can use it. By inserting the chip into the holder and selecting the measurement process on the computer, the system provides the chip's characteristics.

Below are the results and technical specifications derived from the developed prototype system. Currently, we are rigorously testing the printed circuit board (PCB).

Voltages:

We observed an approximately $0.75V$ output voltage from the InAmp, even when the input voltage (Vin) was at zero, limiting the system's voltage measurement range to values exceeding $0.75V$. This issue may be attributed to the InAmp configuration with a single supply (grounding V_{s-}). Dr. Shimon Mizrahi recommends employing a high-quality rail-to-rail InAmp, like the AD623, which, as indicated in its datasheet[xii], is capable of outputting within $0.1V$ above ground.

The upper limit results from V-I converter saturation or clipping. This is due to the limitation that the voltage drops across the Device Under Test (DUT) and the voltage across resistor R combined cannot exceed the supply voltage. With our voltage regulator, the maximum DUT voltage is $9V - Vin$, as validated by our measurements.

Currents:

We measured the current range generated by the V-I converter for the DUT and observed that it extends from $120\ nA$ to $0.15\ mA$. While our system can handle a wider range, we narrowed our focus to this span due to the DUT's resistivity range of $10K\Omega$ to $10M\Omega$. The system’s current accuracy compared to the expected values is within $\pm 2\%$ for each measurement.

To assess the precision of the system's measurements, we employed a straightforward approach. We utilized known-resistance resistors and subjected them to different currents generated by the system. By measuring the voltage drops across these resistors and applying Ohm's law, we calculated the resistance. Subsequently, we determined the relative error between this calculated resistance and the established resistance to gauge the accuracy of the system's measurements.

Ohmic Resistor (Measured by a DVM)	**Relative Error (For measurements of our system)**
R=51.2 [KΩ]	6%
R=222.9 [KΩ]	4%
R=691.9 [KΩ]	7%
R=1.05 [MΩ]	7%

The error is, as we can see, less than 10% of the actual resistance.

We designed the system in accordance with the company's specifications, and during the validation process, we ensured its accuracy by conducting tests on resistors. To minimize the risk of damaging new chips, the company has mandated that system testing with undamaged chips should be conducted directly on the PCB.

However, we've assessed defective chips provided by the company. While we cannot derive quantitative data, these tests hold qualitative value, revealing non-linear V-I characteristics and showcasing the complete measurement process output on a specific device.

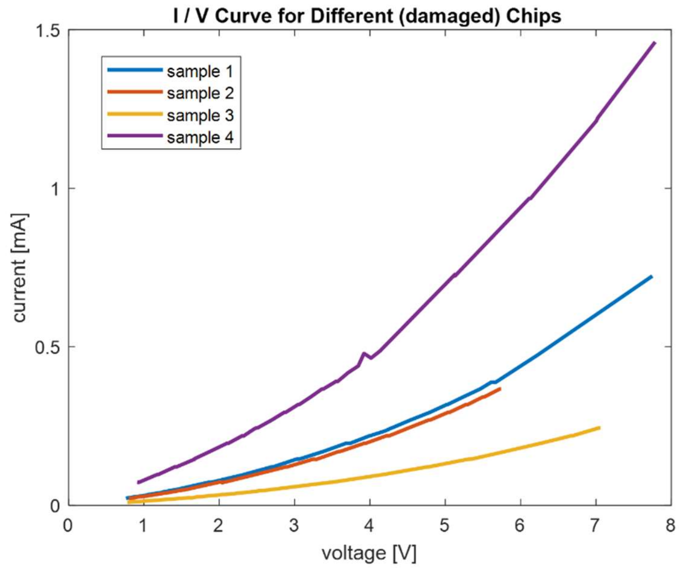

FIGURE 10 THE I/V CURVE

Conclusion and Discussion

Summary of achievements

We have developed a prototype test device for measurement the DC resistance of field emission chips, with the following achieved parameters:

- A resistance measurement accuracy of 90%.
- User-friendly and straightforward in operation.
- Affordability, costing less than $50.

The system can save data, allowing the company to analyse how chips perform based on this parameter. This helps extract insights for chip readability and longevity.

Proposed enhancements to the system

Automatic Polarity Switching

In our system, chip resistivity measurement for reverse-bias or forward-bias requires correct chip alignment on the base. Enhancements can be made by linking the chip base to a relay in the circuit, enabling program-controlled management instead of manual adjustment by the technician.

Eliminating PC Dependency

Currently, the system relies on a PC for test setup and data collection. However, when the system transitions into mass production, we have the potential to remove the need for a PC connection by integrating a display for result presentation. It's important to note that this modification would eliminate the possibility of data collection.

References

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[xii] AD623 Datasheet mailto:https://www.analog.com/media/en/technical-documentation/data-sheets/ad623.pdf.