High Precision Small Current Amplifier with Automatic Gain Control in Integrated Semiconductor Parameter Analyzer

UNIVERSITY OF TURKU
Department of Future Technologies
Master's thesis

WANG Wengang

Supervisors:
Hannu-Pekka Hedman
Research Professor Wan Jing

UNIVERSITY OF TURKU
Department of Future Technologies

WANG Wengang: High Precision Small Current Amplifier with Automatic Gain Control in Integrated Semiconductor Parameter Analyzer

Master's thesis, 73 p., 0 app.p.
Software Engineering, Embedded Electronics, and Communication Technology
September 2019

Semiconductor is widely used in integrated circuits, power and lighting devices; precise measuring of electric facilities of electronic devices such as diode, triode, MOS transistor and optoelectronic devices is very important in semiconductor research and circuits or systems design, the measuring approach includes DC, pulse and C-V measurement. The instrument used to analyze electric facilities of semiconductor devices is called semiconductor parameter analyzer, it is the key of analyzing semiconductor devices, which have high market value.

Currently most of the semiconductor parameter analyzer is imported from the United States, such as Keithley 4200 series of Tektronix® and B1500 series of Keysight®. Keithley 4200A-SCS parameter analyzer delivers synchronizing current-voltage (I-V), capacitance-voltage (C-V) and ultra-fast pulsed I-V measurements; Keysight® B1500A parameter analyzer delivers current-voltage (IV) measurement of spot, sweep, sampling and pulse, Quasi-Static Capacitance-Voltage (QS-CV) measurement, advanced pulsed IV and ultra-fast IV measurement. Small current amplifier is the key unit of semiconductor parameter analyzer, which is also the keystone and difficulty of its development. Small current amplifying is to transform small current signal into voltage and frequency signal, make it easier for the instrument's monitoring and display. Small current signal is dedicated, so there are some obstacles when we design the small current amplifier. This design is the key procedure of the analyzer's development.

In this design we'd like to amplify the small current by I/V transform, it can respond quickly with wide and adjustable range of measurement. Its input bias current and impedance can satisfy our requirement when seriously select the amplifier and strictly follow the technology process.

The testing result indicates that the smallest detected current of the amplifier reaches pA order of magnitude, which is a competent value compared with the current analyzer, while its cost is much lower (hundredths of it) and it is portable.

Keywords: Small Current Amplifying, Automatic Gain Control, Parameter Analyzer, Raspberry Pi

TURUN YLIOPISTO
Tulevaisuuden teknologioiden laitos

WANG Wengang: Korkean tarkkuuden pieni virranvahvistin, jossa on automaattinen tehonsäätö integroidussa puolijohdeparametrianalysaattorissa

Diplomityö, 73 s., 0 liites.
Ohjelmistotekniikka, sulautettu elektroniikka ja tietoliikennetekniikka
Syyskuu 2019

Puolijohteita käytetään laajalti integroiduissa piireissä, teho- ja valaistuslaitteissa. Elektronisten laitteiden, kuten diodin, triodin, MOS-transistorin ja optoelektronisten laitteiden sähköisten ominaisuuksien tarkka mittaus on erittäin tärkeää puolijohteiden tutkimuksessa ja piirien sekä järjestelmien suunnittelussa. Mittausmenetelmä sisältää DC-, pulssi- ja C-V-mittauksen. Puolijohdelaitteiden sähkölaitteiden analysointiin tarkoitettua välinettä kutsutaan puolijohdeparametrianalysaattoriksi. Se on avain analysoitaessa puolijohdelaitteita, joilla on suuri markkina-arvo.

Tällä hetkellä suurin osa puolijohdeparametrianalysaattorista tuodaan Yhdysvalloista, kuten Keithley 4200 -sarja Tektronix®- ja B1500-sarjasta Keysight®. Keithley 4200A-SCS -parametrianalysaattori mahdollistaa synkronoidun virta-jännite (I-V), kapasitanssi-jännite (C-V) ja erittäin nopeita pulssitettuja I-V-mittauksia; Keysight® B1500A -parametrianalysaattorilla voi tehdä virta-jännite (I-V) mittauksen pisteen, pyyhkäisyn, näytteytyksen ja pulssin muodossa sekä kvasi-staattisen kapasitanssin (QS-CV) mittauksen, kehittyneen pulssin IV ja erittäin nopean IV-mittauksen. Heikkovirtavahvistin on puolijohdeparametrianalysaattorin avainyksikkö, joka on myös sen kulmakivi ja vaikea toteuttaa. Vahvistimen tarkoituksena on muuttaa pieni virtasignaali jännite- ja taajuussignaaliksi, helpottaa laitteen monitorointia ja tuoda se näytölle. Pieni virtasignaali on erityislaatuinen, joten heikkovirtavahvistimia suunniteltaessa on joitakin esteitä. Tämä on analysaattorin suunnittelun keskeinen osa.

Tässä suunnittelussa haluamme vahvistaa pienen virran I/V-muunnoksella. Se voi reagoida nopeasti laajalla ja säädettävällä mittausalueella. Sen syöttöarvo ja impedanssi voivat täyttää vaatimuksemme, kun valitsemme harkitusti vahvistimen ja noudatamme tiukasti teknologiaprosessia.

Prototyyppikokeiden tulokset osoittavat, että prototyypin heikkovirta- vahvistinmoduulin vähimmäis mitattavissa oleva virta saavuttaa pA-tason, joka on pätevä arvo verrattuna nykyiseen analysaattoriin, kun taas sen hinta on paljon pienempi (sadasosa siitä) ja se on kannettava.

Avainsanat: Pieni virranvahvistus, automaattinen vahvistuksen ohjaus, parametrianalysaattori, Raspberry Pi

图尔库大学

未来科技系

王文纲: 应用于半导体电学测量系统的高精度自动量程电流放大器

硕士论文，共 73 页，0 附录，
涉及软件工程，嵌入式电子和通信技术
写于 2019 年九月

半导体器件的应用广泛，广泛应用于集成电路，功率器件，发光器件；对电子器件，如二极管，三极管，MOS 晶体管和光电器件的电学特性的精确测量在半导体器件研究和电路系统设计等领域都至关重要，其测量方法包括直流，脉冲和电容-电压测量等。表征半导体器件电学特性的仪器称为半导体参数分析仪，它是表征半导体器件的关键手段，具有巨大的市场应用价值。

目前大部分的半导体参数测量仪依赖进口，例如美国 Tektronix® 公司的 Keithley 4200 和 Keysight®（前 Agilent）公司的 B1500 半导体参数综合测量仪。Keithley 4200A-SCS 参数分析仪可提供同步电流-电压（I-V）、电容-电压（C-V）和超快脉冲 I-V 测量；Keysight B1500A 半导体器件参数分析仪可以进行精确的电流-电压（IV）测量，支持点测量、扫描测量、采样和脉冲测量，支持准静态电容-电压（QS-CV）测量，可以进行先进的脉冲 IV 测量和超快 IV 测量。微弱电流放大器是半导体参数分析仪的核心部件，也是树莓派半导体测量仪研发的关键难点。微弱电流放大是把微弱的电流信号变成电压或者频率信号，从而方便仪表的显示及监控。弱电流信号极易受到外界干扰，设计稳定、可靠的弱电流放大器有一定的技术难度。本课题的顺利展开，是整个树莓派测量系统研发的关键所在。

本课题拟采用 I/V 转换的思路对微弱电流信号进行放大，其具有响应速度快，量程范围宽（可调）等特点，只要慎重选择运算放大器，且在工艺上严格要求制作，其零点漂移，输入阻抗均能满足一般的要求。

样机实验结果表明：试制的微弱电流放大模块最低可测量电流达到 pA 级，相较于现有测量仪，新型测量仪的测量精度可以与之相媲美，而成本将大为降低（百分之一），且体积小巧（相当于平板电脑尺寸），便于携带。

关键词：微弱电流放大，自动增益控制，半导体参数分析仪，树莓派

TABLE OF CONTENTS

TABLE OF FIGURES

TABLE OF ACRONYMS

AGC	Automatic Gain Control
CMOS	Complementary Metal Oxide Semiconductor
CMRR	Common-mode Rejection Ratio
DAC	Digital to Analog Converter
EMI	Electromagnetic Interference
GPIO	General-purpose Input/Output
I^{2}C	Inter-Integrated Circuit
IGFET	Insulated-Gate Field Effect Transistor
JFET	Junction Field Effect Transistor
LAN	Local area network
MCU	Microcontroller Unit
MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor
PCB	Printed Circuit Board
PoE	Power over Ethernet
RF	Radio Frequency
SCL	Serial Clock
SDA	Serial Data
SMBus	System Management Bus
SMD	Surface Mounted Device
SMU	Source Measurement Unit
SNIR	Signal Noise Improvement Ratio
SPI	Serial Peripheral Interface
VCC	Volt Current Condenser

1 INTRODUCTION

Semiconductor parameter analyzer (instrument analyzer) is a testing equipment which integrate all kinds of measuring and analyzing function. It can precisely perform current-voltage (I-V), capacitance-voltage (C-V), capacitance-frequency (C-f) and capacitance-timing (C-t) measurement, then analyze the measurement result efficiently and smoothly, so that to finish the semiconductor parameter test. Semiconductor parameter test is a fundamental measurement to determine semiconductor's characteristic and its production way. In parameter testing, we usually need to implement IV measurement, including the small current measurement down to fA (femto amp) resolution and CV measurement up to 1 MHz, then analyze the main characteristic and parameters. Although the primary goal of developing semiconductor parameter analyzer is to testing semiconductor devices, due to its excellent performance, powerful function and outstanding usability, it has been widely used in all kinds of material, instrument and electronic devices for displaying its IV and CV characteristic [1].

Semiconductor parameter analyzer can provide higher performance, usability and efficiency for displaying task. It integrates all kinds of measuring resources, which can easily perform IV and CV measurement without collecting or integrating instruments such as power supply, voltmeter, current meter, LCR meter and switch matrix, etc. The main measuring devices of parameter is Source/ Measurement Unit (SMU). SMU is a measuring module which integrate the function of voltage supplier and current supplier in one single module. It can precisely force voltage or current and simultaneously measure precise voltage and/or current. SMUs are used for test applications requiring high accuracy, high resolution and measurement flexibility. Such applications include I-V characterizing and testing semiconductors and other nonlinear devices and materials, where sourcing voltage and current source span across both positive and negative values [2]. Since the parameter analyzer tightly integrates the power supply and measuring circuits, it can enable higher precision, resolution and lower measuring error compared with measurement using independent instrument.

Besides, parameter analyzer also has analyzing function, which enable users to quickly check and analyze the measuring results on displayer alternatively. Due to the multiple function of semiconductor parameter analyzer, it is suitable for all kinds of measuring environment from exploratory analysis to automated testing.

With the quick development of computer application technology, microcontroller based on singlechip to collect data, the use of industrial serial touch screen instead of PC for data display and analysis, has become a development trend in the industry. Compared with PC, industrial touch screen not only has great advantage in price, but also more beautiful and easy to carry [3].

1.1 Current Semiconductor Parameter Analyzer

Nowadays, Tektronix® and Keysight Technologies® dominate the market of high-sensitivity semiconductor parameter analyzer. Tektronix® developed its Keithley 4200A-SCS parameter analyzer. It delivers synchronizing current-voltage (I-V), capacitance-voltage (C-V) and ultra-fast pulsed I-V measurements. The DC current-voltage (I-V) range is 10 aA to 1 A from 0.2 μV to 210 V; the capacitance-voltage (C-V) range is ±30V DC bias from 1 kHz to 10 MHz; the pulsed I-V range is ±800 mA, ±40 V with 200 MSa/sec (5 ns sampling rate) [4].

Keysight Technologies® also developed its B1500A semiconductor parameter analyzer. It can make current-voltage (I-V) measurement of spot, sweep, sampling and pulse in the range of 0.1 fA to 1 A from 0.5 μV to 200 V. Besides, it can make AC capacitance measurement in multi frequency from 1kHz to 5MHz and it has Quasi-Static Capacitance-Voltage (QS-CV) measurement capabilities. Its pulsed IV measurement capability is also from minimum 5 ns sampling interval (200 MSa/sec) and it has up to 40 V high voltage pulse forcing [5].

1.2 Our Integrated System Based on Raspberry Pi

In recent years, with the rapid improvement of processor performance and the development of open source hardware, ultra-small computers such as Raspberry Pi with performance close to ordinary PCs and capable of running general-purpose operating systems have emerged. These computers are low in price, small in size, low in power consumption, and have hardware expansion interfaces. They have great potential in replacing traditional embedded intelligent hardware and improving system software and hardware scalability. Using them as the control component of embedded system can eliminate the work of operating system migration and drive development. In this project, we build the hardware and software user interface of the analyzer based on Raspberry Pi. It can rival the current semiconductor parameter analyzer in sensitivity. Besides, it also has high reliability.

In this project, we design and manufacture a portable semiconductor parameter analyzer for low current. It consists of the Raspberry Pi 3B+ microcomputer, AD/DA converter, power supply module, voltage amplifier, PCF module, high-side current amplifier and ground-side current amplifier. It has DC current-voltage (I-V), pulsed I-V and capacitance-voltage (C-V) measurement capabilities. The analyzer can measure different kinds of diode and triode semiconductor devices, which is cheap and precise. Besides, we will add function such as remote control in the future. We forecast this analyzer has a bright prospect and high market demand.

1.3 Small Current Amplifier

According to the theory of small current measurement technology, the amplification of small DC current signals usually takes three methods: integrating amplifier, I/F amplifier and I/V amplifier. Since the integrating amplifier reflects the relationship between the output voltage of the amplifier and the accumulated charge of the integrating capacitors in a certain period of time, as long as the integrating capacitor medium is stable, the leakage current is small enough, and the input bias current of the selected operational amplifier is less than the accuracy required by the measured current, then the amplifier has enough measurement accuracy. Therefore, this kind of amplifier has the advantages of high measurement accuracy and small zero drift. However, the amplifier has long response time and is not suitable for dynamic online measurement. Although the I/F amplifier is faster than the integrating amplifier and the zero drift is relatively small, the measurement range is narrow, the circuit design is complicated and debugging is troublesome. The I/V conversion amplifier has the characteristics of fast response and wide measuring range (adjustable). As long as the operational amplifier is carefully selected and strictly fabricated in the process, its zero drift and input impedance can meet the general requirements. Therefore, it is widely used in measuring instruments.

Current-voltage (I/V) conversion amplifiers are divided into two types: shunt amplifiers and feedback amplifiers. Feedback amplifier has low input impedance and small output offset voltage, for example, using the same operational amplifier (OPA111BM) and 1GΩ transimpedance gain, the output voltage offset of the shunt amplifier is ±251mV, while the output voltage offset of the feedback amplifier is

±1.5mV. However, limited by operational amplifier, the measured current cannot be greater than 5mA. For high transimpedance gain, high quality resistance with high resistance value is needed [6].

The circuit of basic small current amplifier can be seen from Figure 1. The amplifier and circuit form a typical inverting amplifying circuit, but without input resistance. It is actually an I-V inverter, which has some following differences:

- Has protecting guard
- Feedback resistance R_{fb} is extremely large, about 10 to the power of 12, which is 1 TΩ
- Has feedback capacitance C_{fb}, which can be used to allocate voltage with input equivalent capacitance, so that to improve the response ability

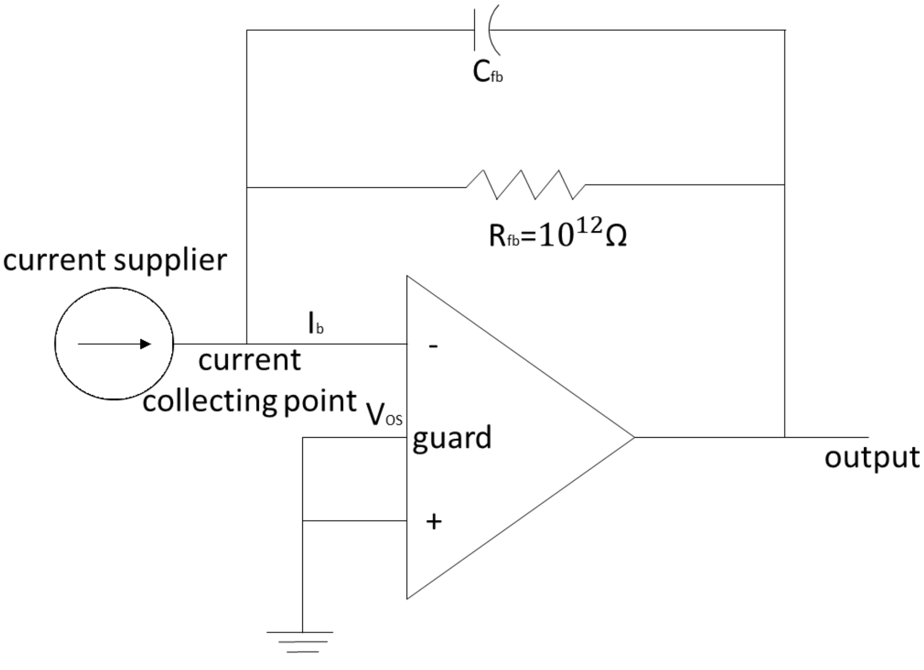


Figure 1: Typical circuit of small current amplifying [7]

Current collecting point is actually a virtual ground. As long as the operational amplifier is on working mode, this point will keep in ground potential. When the input current comes, the current will not flow into the negative side of the operational amplifier, so all of the current flow into R_{fb}, which makes the output voltage drop, the voltage drop is the product of the input current and R_{fb}. So this point is current collecting point, several current stream is collected in this point, but the voltage here will not change with the input current, always in ground potential, so it is called virtual ground.

Since R_{fb} is very large, up to 1 TΩ, the input current of 1 pA will cause output voltage of 1V, in this way, we can get amperemeter with measuring scope of 2 pA by using voltmeter with measuring scope of 2V.

Then we will introduce the input bias current of the operational amplifier, Input bias current I_b is due to the existence of leakage current in both input terminals of the operational amplifier. We can understand in this way, each input terminal of the ideal operational amplifier is connected in series with a current source, which can be seen in Figure 2, and the current values of the two current sources are generally different. That is to say, the real operational amplifier will have current flow into or out of the input terminals of the operational amplifier (not quite the same as the virtual open circuit of the ideal operational amplifier). Then input bias current is defined as the average of these two currents. Input offset current is defined as the difference between the two currents [8].

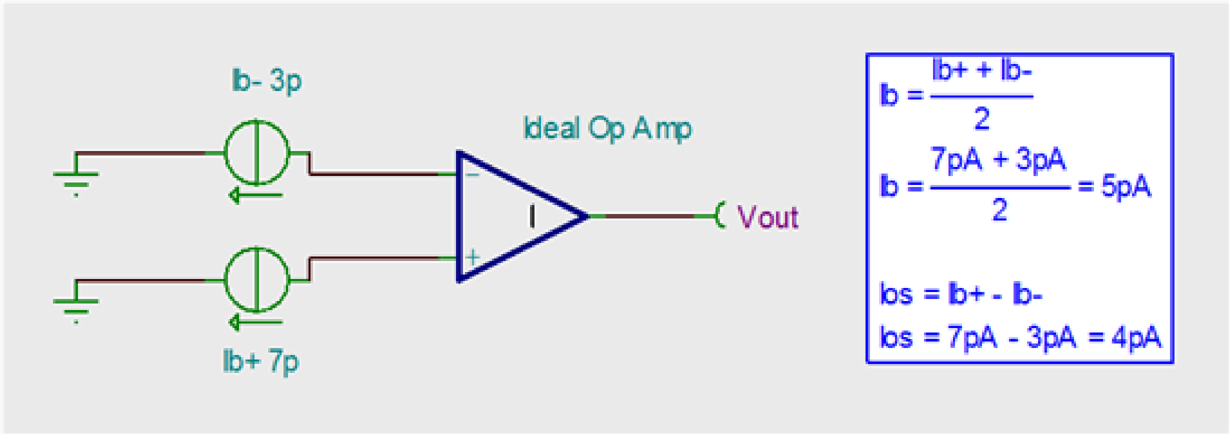


Figure 2: Equivalent model of input bias current [8]

Therefore, in order to use feedback resistance with high R_{fb}, the input-bias current of the operational amplifier need to be very small, much smaller than scope of 2 pA. Otherwise when the load circuit is open, entire I_b go through R_{fb} , 1pA will generate wrong output of 1V, which is not permitted.

In fact, I_b is always here, so we need compensation circuit and zeroing circuit. Even though, it is very hard to get high indicators, because I_b varies a lot, especially with temperature, which will greatly influence the testing result.

Therefore, I_b is a very important index to consider when we make small current testing, we must select operational amplifier with low input-bias current.

When the input bias current mentioned above flows through the external resistor network, it will be converted into the offset voltage V_{OS} of the operational amplifier. V_{OS} between two inputs will also effect the testing precision. V_{OS} is directly added to the output signal. Suppose V_{OS}=10mV, the original output is 1V, after adding V_{OS}, the output is 1.01V, forming an error rate of 1%. Suppose the input current is small, which is 0.1 pA, then the calculated output is 0.1V, actual output is 0.11V, the error rate rise to 10%. Therefore, V_{OS} should be as low as possible. In fact, when we generate small current, we need small voltage, so V_{OS}'s effect is much stronger, which also require operational amplifier have small V_{OS}.

If V_{OS} is not small enough, we can eliminate it mostly by compensation circuit. But V_{OS} varies with temperature, which make temperature index the most important indicator of V_{OS}.

The structure of small current amplifier varies a lot, some are based on electrometer transistor, some are based on special bipolar transistor, some are based on Junction Field Effect Transistor (JFET) or Insulated-Gate Field Effect Transistor (IGFET), others are based on changeable capacitance. Since electrometer transistor is huge, short life, takes long time to stabilize and needs complicated power supply, it is gradually replaced by some operational amplifier with high input resistance and performance [9].

1.4 Small Current Amplifier in Semiconductor Parameter Analyzer

In semiconductor device testing, many testing cases need to measure current in pA and μA magnitude, such as: the reverse leaking current of transistor, cut-off current, input bias current of operational transistor, cut-off leaking current of simulated switch, etc. These current are very small, which need to be amplified by corresponding detecting circuit, then transfer to the scope where common voltmeter/amperemeter or A/D converter can receive [10].

Recent years, Signal Noise Improvement Ratio (SNIR) regarding small current can reach to 10^{17}. The domestic institute which is good at this area is Nanjing University, its ND-051 small signal detector is used by at least 76 domestic institutes. But it is expensive, from thousands of RMB to tens of thousands of RMB. Such as HB-831 pA order of magnitude current amplifier, HB-834 four-channel pA order of magnitude current amplifier and HB-834 eight-channel pA order of magnitude current amplifier. Their prices are 4100 RMB/unit, 13000 RMB/unit and 22000 RMB/unit respectively. Therefore, it is vital to develop small current amplifier with high precision, long life, low cost and simple circuit.

In our semiconductor parameter analyzer we have two kinds of small current amplifier, one is called ground-side current amplifier, which is similar to the I-V converter discussed above, but due to its limited performance, it cannot detect very small current; another is called high-side current amplifier, which will be discussed in next Chapter.

2 THE SMALL CURRENT AMPLIFIER CIRCUIT DESIGN AND ITS SYSTEM APPLICATION

In this Chapter the hardware part of the designed small current amplifier will be discussed. Firstly, the theory diagram of the overall system is shown. Then, the core function of the small current amplifier in the system is discussed. Finally, circuit design of amplifier and corresponding PCF module is presented.

2.1 Theory Diagram of the Overall System and the Core Function of Amplifier

The principle diagram of the designed semiconductor parameter analyzer can be seen in Figure 3. We use Raspberry Pi 3B+ as the Microcontroller Unit (MCU); power supply management unit includes power supply module and V_A module; D/A module is used to transfer the digital control signal of the Raspberry Pi into analog signal, then the signal can control all kinds of measuring module in the terminal; A/D module is used to transfer the analog signal detected by measuring module into digital signal, then the signal can be read by Raspberry Pi; the whole system has four kinds of measuring function, the DC current measuring of transistor and C-V measurement is implemented by me and my colleague students, the other two functions will be realized by our successors, which is filled in gray.

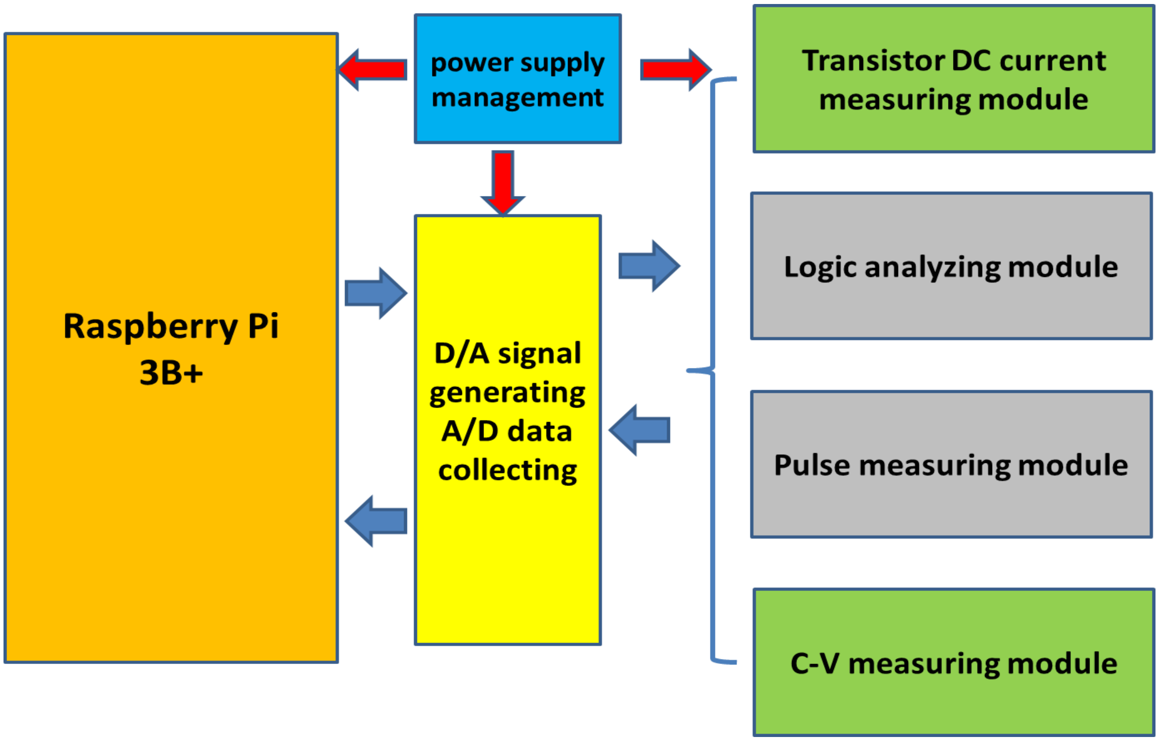


Figure 3: Principle diagram of the designed semiconductor parameter analyzer

The principle diagram of the designed transistor DC measuring module can be seen in Figure 4. For D/A module we use DAC8534, which is a quad channel, 16-bit, serial input DAC working in 2.7V to 5.5V [11]; for power supply module we use ±15V boost module, this module can work in wide range of input voltage from 4V to 30V. Besides, this module has automatic step-up, step-down and voltage regulating function. Any input voltage turbulence from 4V to 30V will not inflect output voltage, which is very suitable for working in tough environment and provide a dependable power supply solution for our portable semiconductor parameter analyzer; the function of V_A module is to scan the voltage from -10V to 10V so that to analyze the I-V characteristics of the testing devices. Since the current flow out of the semiconductor devices is very small, we need to amplify the output current by current amplifier, which will be discussed in next section. After being amplified, the signal can be detected by A/D module. For A/D module we use AD7606, which is an 8-channel DAS with 16-bit, bipolar and simultaneous sampling ADC [12]. Raspberry

3B+ is the latest revision of their third-generation single-board computer, it has 1.4 GHz 64-bit quad-core processor, dual-band wireless LAN, Bluetooth 4.2/BLE, faster Ethernet, and Power-over-Ethernet support (with separate PoE HAT) [13].

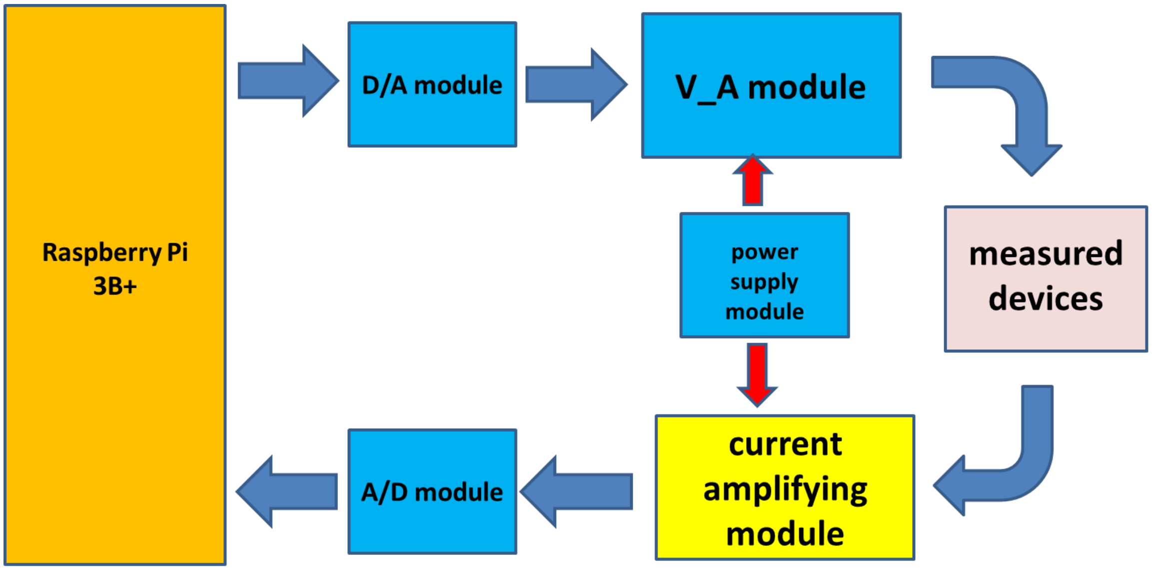


Figure 4: Principle diagram of the designed transistor DC measuring module

2.2 Circuit Design of Current Amplifier and Corresponding PCF Module

Since semiconductor devices such as triode is a three-terminal device, there are two current flows go through it - working current and switching current. The working current can be amplified by normal current amplifier since it is not too small, the structure of the current amplifier can be seen in Figure 1, and in our project we call it ground-side current amplifier. The switching current is much smaller, which requires our amplifier has very small input bias current and input offset current, in this project we call it high-side current amplifier, this current amplifier is based on instrumentation amplifier. It is an extremely precise differential voltage amplifier that is derived from an operational amplifier but integrates key components inside the amplifier. The highly integrated structure gives it an incomparable advantage of traditional operational amplifier. In recent years, instrument amplifiers have been widely used in data acquisition, process control, sensor signal amplification, and precision medical instruments due to their excellent electronic characteristics.

Instrumentation amplifier features

Instrumentation amplifiers outperform traditional operational amplifiers in many ways [14], as follows:

- Very high common-mode rejection ratio, with a typical CMRR of 70 to 100 dB
- Very high (ideally infinite) common mode and differential mode input impedance, typical value of $10^9 \sim 10^{15}\Omega$
- Very low (ideally zero) output impedance
- Precise and stable gain, which can be set internally or via external gain resistance, generally ranging from 1 V/V to 10^3 V/V

Structure and principle of instrumentation amplifier circuit

Differential amplifier is the electronic basis of instrumentation amplifier, its structure can be seen in Figure 5 (a), with one output end and two input ends; if there are two signals V1 and V2, one of them is applied to the inverting terminal and another is applied to the non-inverting terminal.

Using the superposition principle to solve V_O, let $V_1 = 0$ and $V_2 = 0$, respectively, then we can get:

$$V_O = \frac{R_2}{R_1}\left(\frac{1+\frac{R_1}{R_2}}{1+\frac{R_3}{R_4}}V_2 - V_1\right) \tag{1}$$

If several resistors in equation (1) satisfy the following bridge balance conditions:

$$\frac{R_4}{R_3} = \frac{R_2}{R_1} \tag{2}$$

At this point, the circuit becomes a "true" differential amplifier, that is, its output signal is proportional to the difference between its two input signals, that is:

$$V_O = \frac{R_2}{R_1}(V_2 - V_1) \tag{3}$$

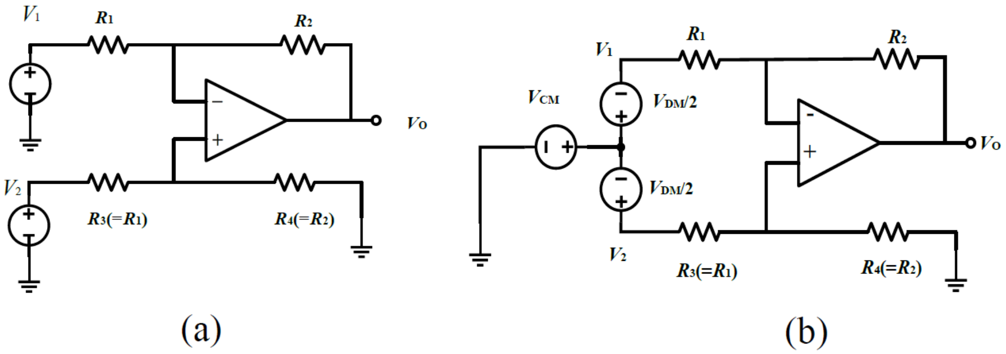


Figure 5: (a) Differential amplifier schematic diagram; (b) Circuit diagram after introducing common mode and differential mode components

As shown in Figure 5(b), the differential mode component and common mode component are introduced into the circuit and defined as:

$$V_{DM} = V_2 - V_1 \tag{4}$$

$$V_{CM} = \frac{V_1 + V_2}{2} \tag{5}$$

At this point, equation transformation can be used to obtain:

$$V_1 = V_{CM} - \frac{V_{DM}}{2} \tag{6}$$

$$V_2 = V_{CM} + \frac{V_{DM}}{2} \tag{7}$$

This results in a true differential amplifier circuit that responds only to the differential mode component V_{DM} at the input and is not affected by the common mode component V_{CM} at all. At this time, if a low-level differential signal is superimposed on a high-level common-mode signal, the useful differential signal can be extracted from the high common-mode signal environment.

The instrumentation amplifier is built on these characteristics of the differential amplifier. After proper modification, the differential circuit shown in Figure 5(a) can initially meet the technical requirements of the instrumentation amplifier. However, the load on the power supply will reduce the source voltages V_1 and V_2, which in turn causes a drop in CMRR. These defects can be eliminated by placing a follower amplifier with high input impedance before the input terminal of the amplifier, thus forming the most classic three-operational instrumentation amplifier structure.

The typical structure of the common three-operational instrumentation amplifier circuit is shown in Figure 6, which mainly includes two-stage differential amplifier circuit. A_1 and A_2 are operational amplifiers with non-inverting differential inputs, which are usually called first stage or input stage. The non-inverting input can greatly improve the input impedance of the circuit and reduce the circuit attenuation of the input weak signal; the differential input makes the circuit only amplify the differential mode signal, while the common mode input signal only follows, thereby greatly increasing the CMRR. Therefore, in the differential amplifying circuit with operational amplifier A_3 as the second stage, the accuracy matching requirements of resistors R_3 and R_4, R_f and R_5 are greatly reduced on the premise of keeping the CMRR requirements unchanged, so that the instrumentation amplifier circuit has higher common mode rejection capacity than the single differential amplifying circuit.

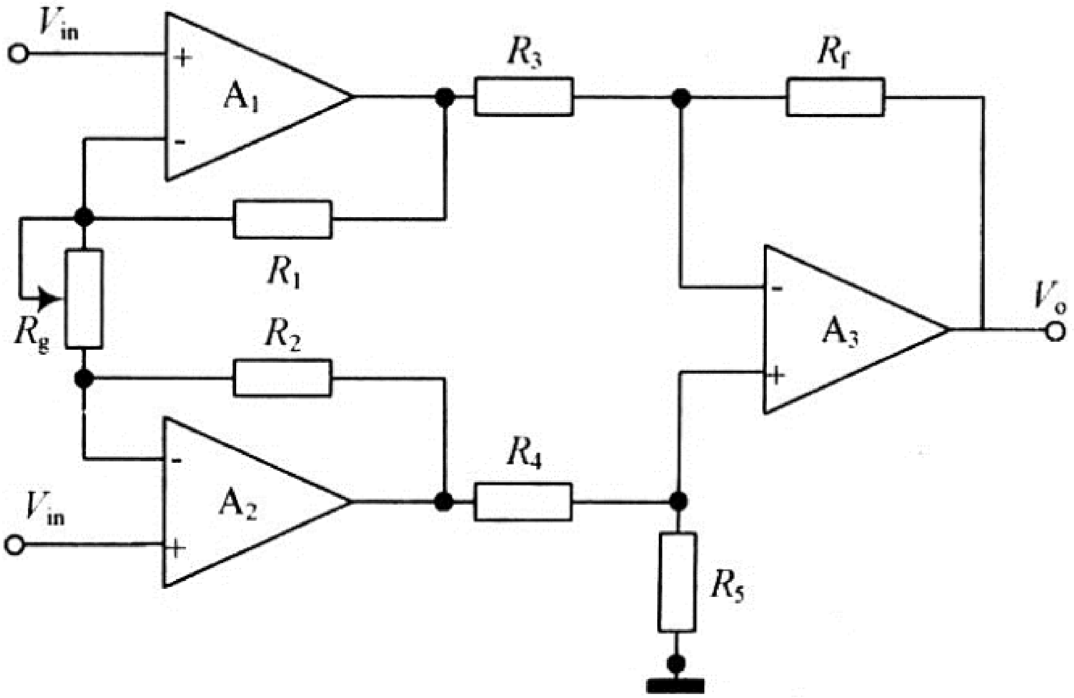


Figure 6: The typical structure of the classical triple operational amplifier IA [15]

At this time, if $R_1 = R_2$, $R_3 = R_4$, $R_f = R_5$, then the gain of the circuit in Figure 6 is:

$$G = \left(1 + \frac{2R_1}{R_g}\right)\frac{R_f}{R_3} \quad (8)$$

As can be seen from the above equation, when R_1, R_3 and R_f are determined values, the adjustment of the circuit gain G can be realized by changing the resistance of R_g [15].

Design of small current amplifier circuit based on instrumentation amplifier

Generally speaking, there are mainly two ways to implement the instrumentation amplifier circuit: one is the combination of multiple (≥3) discrete electronic components; the other is directly implemented by a single IC (integrated chip). The most common examples are AD622 (Analog Devices) and INA114 (Burr Brown®) [16], both of which contain all components except RG, which can set the gain according to their own needs.

According to our requirements, we use INA116 ultra low input bias current instrumentation amplifier produced by Texas Instruments®. It is a complete monolithic instrumentation amplifier, the amplifier has very low input bias current, the typical value can down to 3fA (25 ℃), and the input bias current does not increase dramatically as the temperature rises to 125 ℃. Besides, it has low offset voltage, the maximum value is 2mV, high common-mode rejection ratio (84 dB) and high input resistance (10^{15} Ω) [17].

Then the circuit diagram of high-side current amplifier can be seen in Figure 7. INA 116PA is the instrumentation amplifier we use; R_S refers to sensing resistance, which the small current goes through; R_L refers to load resistance; R_G is the gain resistance, which can set the current amplification index of the instrumentation amplifier. Gain of the INA116 is set by connecting a single external resistor, R_G, as shown. The gain is:

$$G = 1 + \frac{50k\Omega}{R_G} \tag{9}$$

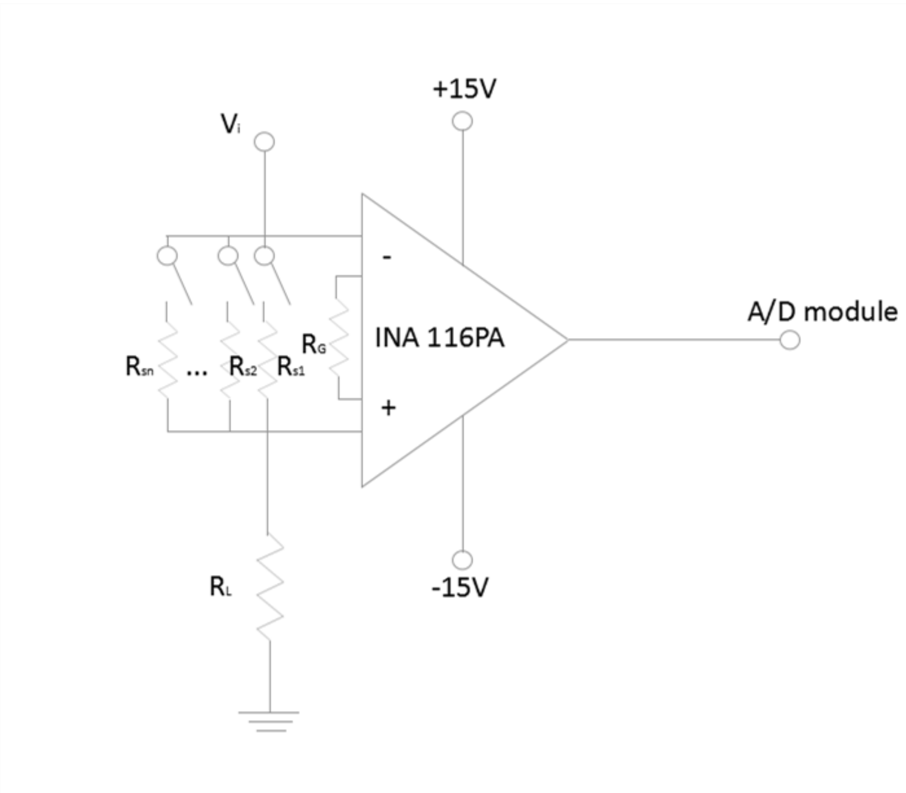


Figure 7: Circuit diagram of the designed small current amplifier

Commonly used gains and resistor value are shown in Table 1. The stability and temperature drift of R_G also affect gain. R_G's contribution to gain accuracy and drift can be directly inferred from the gain equation (1). Low resistor values required for high gain make wiring resistance important. Sockets add to the wiring resistance that will contribute additional gain error in gains of approximately 100 or greater. So in our small current amplifier we use precision resistor as R_G to achieve desired gain as close as possible.

DESIRED GAIN	R_G	NEAREST 1% R_G
1	NC	NC
2	50.00k	49.9k
5	12.50k	12.4k

10	5.556k	5.62k
20	2.632k	2.61k
50	1.02k	1.02k
100	505.1	511
200	251.3	249
500	100.2	100
1000	50.05	49.9
2000	25.01	24.9
5000	10.00	10
10000	5.001	4.99

Table 1: Commonly used gains and resistor value of INA116

We use R_G of 50 Ω and 500 Ω, then according to Table 1, the corresponding amplification index is 1000 and 100. For R_S and R_L we also use precision resistance to guarantee accuracy, By changing R_S/R_L we can allocate the voltage drop of R_S and R_L, in our project we set R_S/R_L as 1/1000 and 1/100 when the amplification index is 1000 and 100, so theoretically output voltage of INA116 is same as the input voltage. By this way we can detect the switching current of the semiconductor devices in a clear and simple method.

Actually the measuring scope of the amplifier will up to 10 orders of magnitude when measuring non-linear devices such as diode, but the A/D module we use is only 16 bit, so in Figure 7 we need different sensing resistance R_S to get different R_s/R_L, so that to amplify or reduce the output voltage of the operational amplifier to make it within the A/D module's acquisition scope. In our project we decide to select each R_S by closing the corresponding relay linked with it. The schematic diagram can be seen from Figure 8. The MS1 to MS8 are relays which can select R_S from 1 Ω to 10 MΩ, each relay can be switched on/off by a corresponding S9013 triode transistor, when the input voltage of its basic electrode is 3.3 V, the relay is switched on, then the R_S linked to the relay is selected, so we have together 8 ports to select R_S; MS9 can select another gain resistance which is 50 Ω, under this circumstance the gain of the INA116 is 1000, we have 1 port to select R_G. V_O_BNC1 is linked to R_L, so that forms a voltage dividing circuit with different voltage allocation. The final work of the high-side current amplifier can be seen from Figure 9.

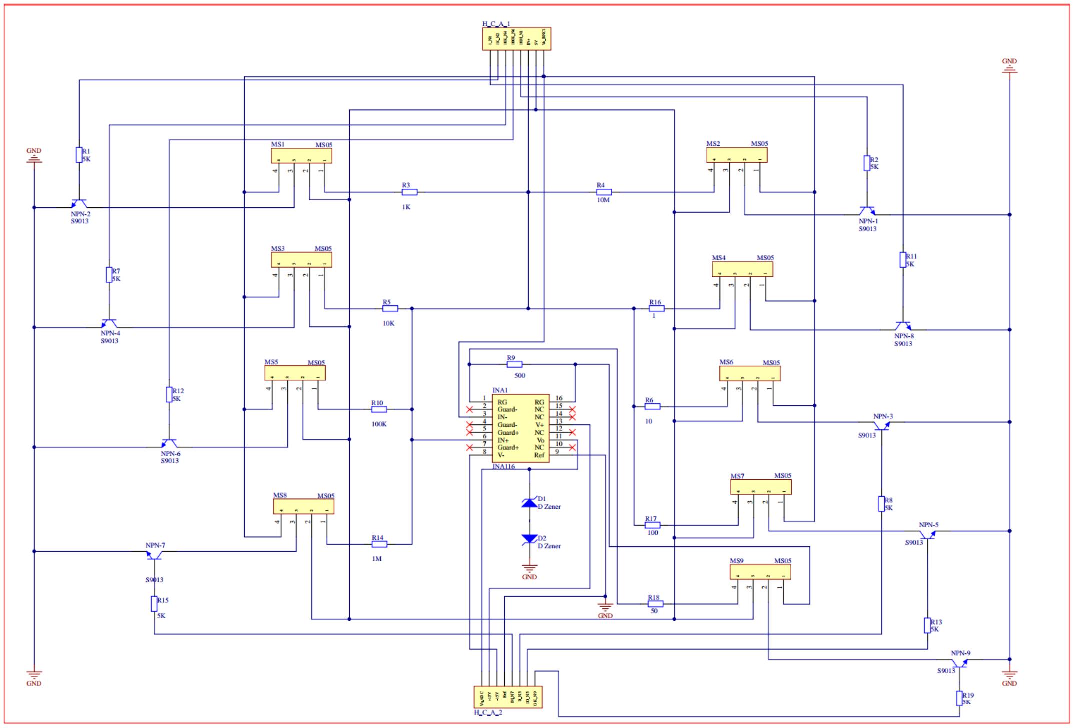


Figure 8: Circuit diagram of the designed high-side current amplifier

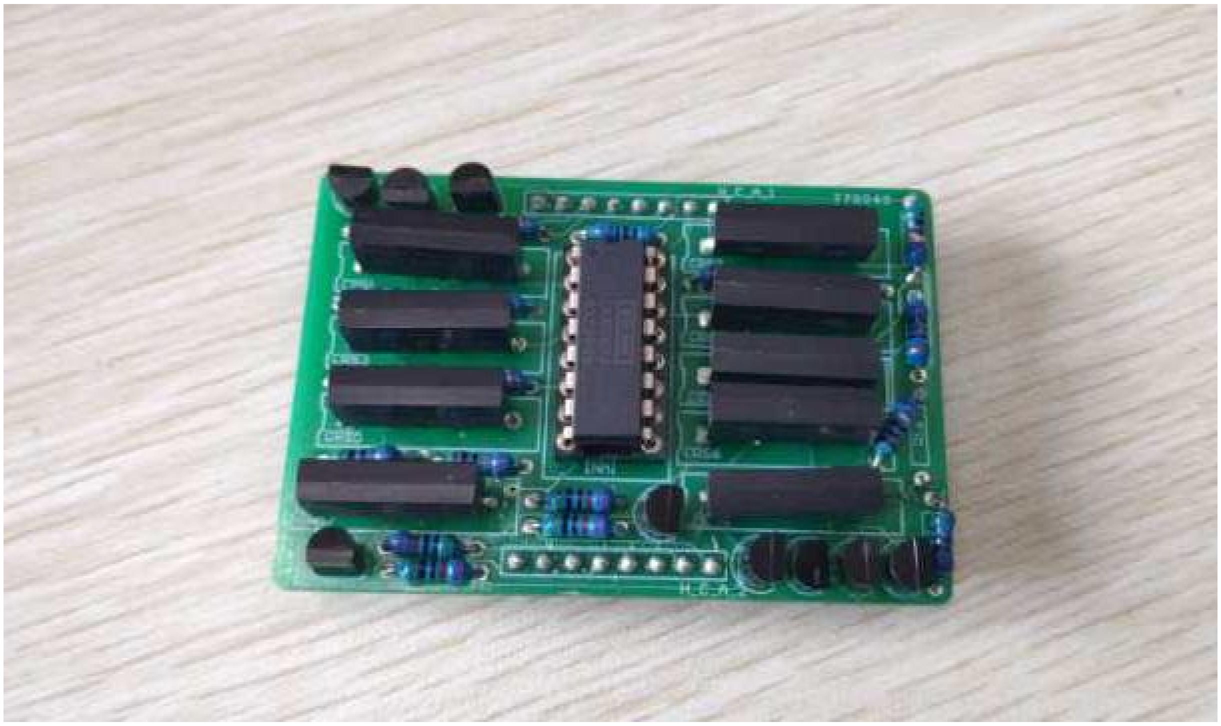


Figure 9: Final work of high-side current amplifier

Since the semiconductor parameter analyzer has to measure and compare the performance of different semiconductor devices at the same time and to measure some semiconductor devices with multi-channels like triode and MOSFET, we have 4 channels of measuring circuit. But the GPIO port of Raspberry Pi is not enough to control so many channels, so we cannot control these circuits with Raspberry's GPIO directly.

Note that Raspberry Pi is a microcontroller which has I^2C interface, and multiple I^2C devices can share a single I^2C bus, so we can choose some I^2C controlled I/O expanders to extend the Raspberry Pi's GPIO port. We use PCF8575 remote 16-bit I^2C and SMBus I/O expander with interrupt output to extend the I/O port of Raspberry Pi. Raspberry Pi works as the master device while PCF module works as the slave in this I^2C topology, Raspberry Pi can enable the bus to transmit data, meanwhile generate clock signal to enable PCF module. Every data transmission to or from the PCF8575 must consist of an even number of bytes. The first data byte in every pair refers to port 0 (P07 – P00), and the second data byte in every pair refers to port 1 (P17 – P10). To write to the ports (output mode), the master first addresses the slave device, setting the last bit of the byte containing the slave address to logic 0. The PCF8575 acknowledges, and the master sends the first data byte for P07 – P00. After the first data byte is acknowledged by the PCF8575, the second data byte (P17 – P10) is sent by the master. Once again, the PCF8575 acknowledges the receipt of the data, after which this 16-bit data is presented on the port lines [18]. The PCF8575 device provides general-purpose remote I/O expansion for most microcontroller families by way of the I^2 C interface [serial clock (SCL), serial data (SDA)] [19]. It has three hardware pins (A0, A1, and A2), which can be used to program and vary the fixed I^2C address and allow up to eight devices to share the same I^2C bus or SMBus. We have totally 4 PCF modules to share the same I^2C bus on the mainboard. The principle diagram of how the Raspberry Pi realize multi-channel measurement can be seen from Figure 10. Since each PCF module has 16-bit quasi-bidirectional I/O port, it can control 2 high-side current amplifier with 8 port, we have 4 ways of measuring channel, which means we need 4 high-side current amplifier, so for this side we need 2 PCF modules to control these measuring channels. The selection of another R_G of these 4 modules is done by another PCF module on the mainboard, which is not shown in the diagram. Note that when powers on PCF8575, the I/O ports are high, but we need low input voltage from I/O ports at the beginning, so we need to initialize the I/O ports as low.

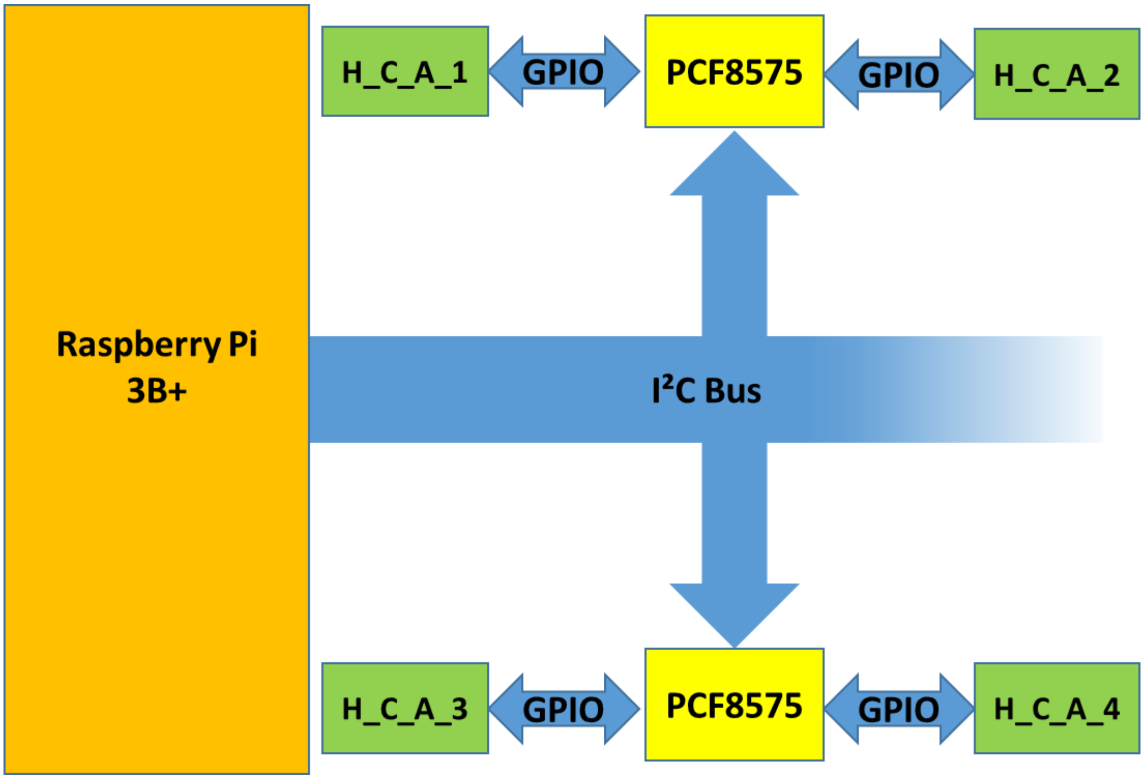
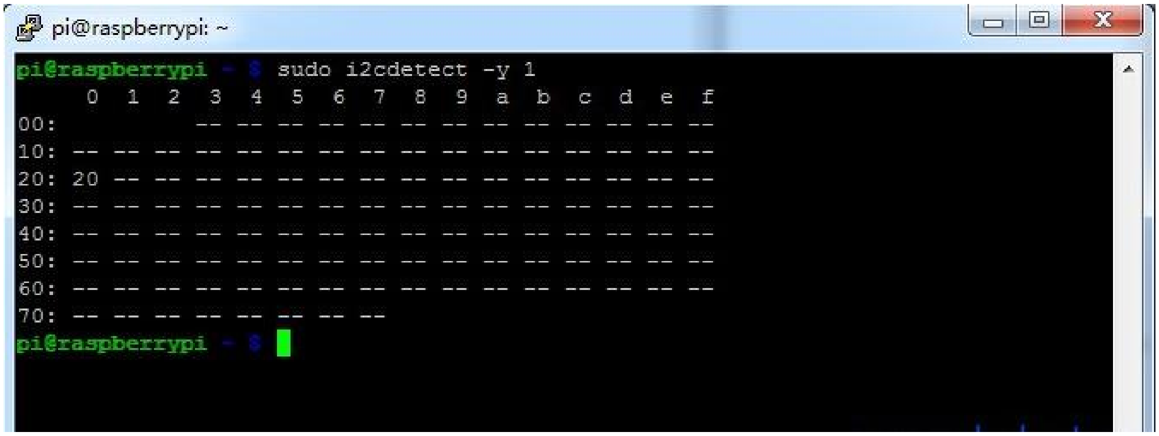


Figure 10: Principle diagram of current amplifier and corresponding PCF module

When start to configure Raspberry Pi and PCF module, we need to connect I2C1_SDA port of Raspberry Pi with SDA port of PCF 8575, connect I2C1_SCL port of Raspberry Pi with SCL port of PCF 8575, besides connect their VCC and GND ports. Then open I^2C function of Raspberry Pi in its configuration window, install I^2C tools package, next in the command-line interface of Raspberry Pi, enter “sudo i2cdetect -y 1” to view the I^2C device, then we can get the address of PCF8575 module in the command window, which can be seen from Figure 11. We can see the address of PCF8575 is 0x20. Since for high-side current amplifier we need totally 2 PCF modules, when two PCF modules work simultaneously, their addresses are set to 0x20 and 0x21 respectively.



```
pi@raspberrypi ~ $ sudo i2cdetect -y 1
     0  1  2  3  4  5  6  7  8  9  a  b  c  d  e  f
00:          -- -- -- -- -- -- -- -- -- -- -- -- --
10: -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- --
20: 20 -- -- -- -- -- -- -- -- -- -- -- -- -- -- --
30: -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- --
40: -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- --
50: -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- --
60: -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- --
70: -- -- -- -- -- -- -- --
pi@raspberrypi ~ $
```

Figure 11: I^{2}C address of PCF module in command-line interface

3 CONTROL AND MEASURE PROGRAM DESIGN OF SMALL CURRENT AMPLIFIER

In this Chapter, the designed control and measure program of small current amplifier will be discussed. Firstly, as we need to select different sensing resistance R_S to amplify or reduce the output voltage of the operational amplifier to make it within the A/D module's acquisition scope, we designed the corresponding program to select proper R_S when the output voltage is beyond A/D module's measuring scope. In other words, we need to make the voltage gain of high-side current amplifier fit with the A/D module's measuring scope; we call this program as automatic gain control function. Secondly, corresponding program to control PCF module is discussed. Finally, a program which can overcome the error when measuring nonlinear devices such as diode transistor will be discussed.

3.1 Automatic Gain Control Function

Current measurement of semiconductor devices has very range dynamic range, generally the lowest detected current will be as low as 1 pA; while the maximum detected current will up to 10 mA. The input signal range of the A/D converter is fixed. If measured in the same range, the weak signal is amplified by an amplifier with a fixed gain, and the sensor signal is highly discrete, which is easy to generate large errors and difficult to achieve accurate A/D conversion. In order to improve the measuring accuracy, it is necessary to switch the measuring range according to the measured value. The existing program-controlled amplification technology can effectively solve this problem.

Automatic Gain Control (AGC) is a control method that automatically adjusts the gain of the amplifier circuit with the signal strength. AGC is a closed - loop electronic circuit, which is usually implemented by negative feedback. It can be divided into two parts: gain controlled amplifier circuit and control voltage forming circuit. Gain controlled amplifier circuit is usually located in the forward path, and the gain of the circuit changes as the control voltage changes. The basic components of the control voltage forming circuit are AGC detectors and low-pass smoothing filters, and sometimes include components such as gates and DC amplifiers [20].

In the AGC, the output signal u_o of the gain controlled amplifier circuit is detected by AGC and filtered by the low-pass smoothing filter to filter out the low-frequency modulation component and noise, thereby generating a voltage for controlling the operation of the gain-controlled amplifier circuit. When the input signal u_i of the gain controlled amplifier circuit increases, u_o and u_c also increase. The increase of u_c reduces the gain of the amplifier circuit, and the change of u_o of the output signal is significantly less than that of the input signal, thus achieving the purpose of automatic gain control. Commonly used amplifier circuit gain control methods are:

- Change the static operating point Q of the triode to change the current amplification factor
- Insert electronically controlled attenuators between the amplifier stages
- Load the amplifier with electrically controlled variable resistors

Nowadays, AGC is widely used in data transmission and communication equipment, such as transmission, reception, signal modulation, and various measuring instruments. Since AGC can keep the output level of the system within a certain range, it is also often called automatic level control.

Suppose the quantization error of the n-bit A/D converter is:

$$\Delta = \frac{REF}{2^{N} - 1} \tag{10}$$

Where REF is the reference level of the A/D converter.

Suppose the analog input voltage of A/D converter is V_i, then the relative error after A/D conversion is:

$$\delta = \frac{REF}{2^{N} - 1} V_i \tag{11}$$

That is: δ is inversely proportional to V_i, which requires that the analog input voltage value m must be amplified in advance to be as close as possible to the reference level REF, so that to fully exert the performance of the A/D converter bits and reduce the quantization error [21].

Just because of the wide range of current value when measuring semiconductor components, the program controlled gain amplification technology is adopted to realize the automatic conversion of measuring range and improve the measuring accuracy.

In this system, the data amplifier AD7606 and the multiplexer switch form the automatic gain control circuit (AGC). The automatic gain control function controls the corresponding relays to switch the gain of the current amplifier from 10^2 V/A to 10^9 V/A, so that to realize wide dynamic range of amplification. The principle diagram of how this automatic gain control function work can be seen from Figure 12. At beginning the function will initialize the port, clock, A/D converter and communication, then the A/D module will do the A/D conversion. If the conversion value is less than the lower limit, then Raspberry Pi will switch to circuit with higher R_S; if conversion value is greater than the upper limit, then Raspberry Pi will switch to circuit with lower R_S. After finishing the A/D conversion, the conversion result will be transmitted to raspberry Pi through SPI interface. The judging principle is whether the output voltage of the amplifier is beyond to A/D module's measuring scope, if so, the function will select smaller R_S to get smaller R_S/R_L so that to reduce output voltage within the A/D's measuring scope. So this is a closed-loop control program, the principle to judge whether the output voltage is beyond A/D module's measuring scope is to check if it is oversampling. If so, then we should reduce the output voltage of amplifier. AD7606 is a 16-bit, bipolar and simultaneous sampling ADC, so its resolution is 65536, but our required resolution is 10 degrees of magnitude. So by increasing its sampling rate, we can realize the requirements, but oversampling will also greatly extend the conversion time, which is not accepted in our project because in order to reduce random error, we need to take the average after sampling 10 times, which will 10 times the delay, this delay will cause great impact on the performance of the analyzer.

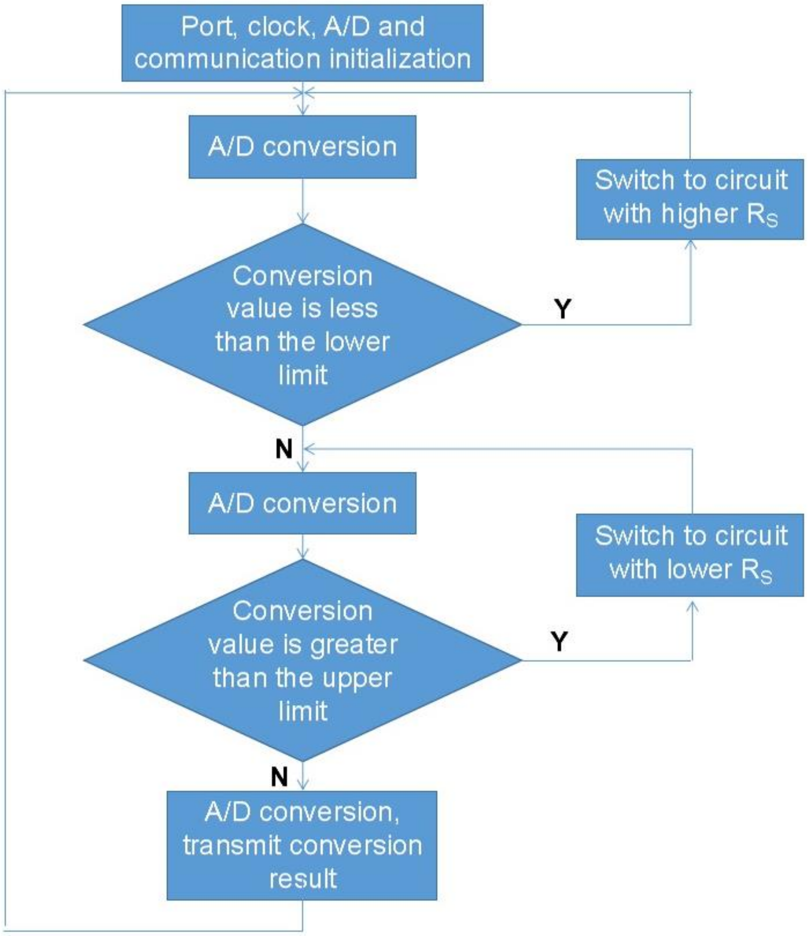
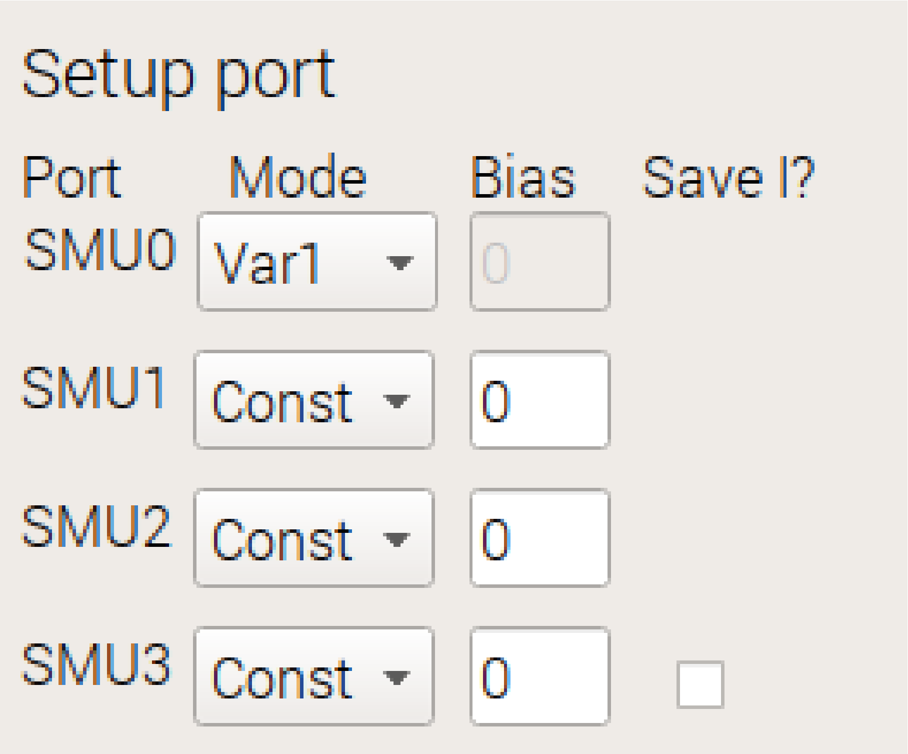


Figure 12: Principle diagram of automatic gain control function

3.2 PCF control Function

When the semiconductor parameter analyzer need to measure and compare the performance of different semiconductor devices at the same time or to measure some semiconductor devices with multi-channels like triode and MOSFET, we need to control the usage of 2 PCF modules, in our program we can control the ports we need to use in the user interface. The design of “Setup port” section can be seen from Figure 13. SMU1 to SMU4 refers to 4 PCF modules since they control all kinds of source measurement unit from high-side current amplifier to ground-side current amplifier. For each port we have selection of Mode, in the drop-down menu we can select Const, Var1 and Var2. Const means there is no output, so all of the ports are closed; Var1 means the first 8 ports connected with one current amplifier is open; Var2 means the last 8 ports connected with another current amplifier is open. When the output is constant, we can set the bias current in the next selection.



Setup port

Port	Mode	Bias	Save I?
SMU0	Var1	0	
SMU1	Const	0	
SMU2	Const	0	
SMU3	Const	0	☐

Figure 13: User interface of PCF control function

3.3 Voltage tracking function in current measurement

When we measure the I-V characteristics of the device, we need to know and control its input voltage. Due to the voltage drop caused by R_S, the voltage allocated to measured device is slightly smaller than the input voltage of the operational amplifier. So in our small current amplifier we will manually increase the input voltage of the operational amplifier to make the input voltage of the measured device satisfy the measuring requirements.

When the measured device is nonlinear such as diode, which can be seen in Figure 14, the I-V characteristics line is not a straight line, so we can not calculate previously to reset the input voltage of operational amplifier to make the input voltage of measured device match the required measuring scope. In our project, we build a function which can track the input voltage of the measured device while measuring current. Firstly, the program will calculate the voltage drop of R_S according to the current go through it. Next, the function will get the input voltage of the measured device by minus input voltage of the operational amplifier with the voltage drop of R_S. Then, the program will calculate the difference between the target input voltage and real input voltage of the measured device. Finally, the function will add the voltage difference to the input voltage of the operational amplifier to make the input voltage of the measured device approach our target value.

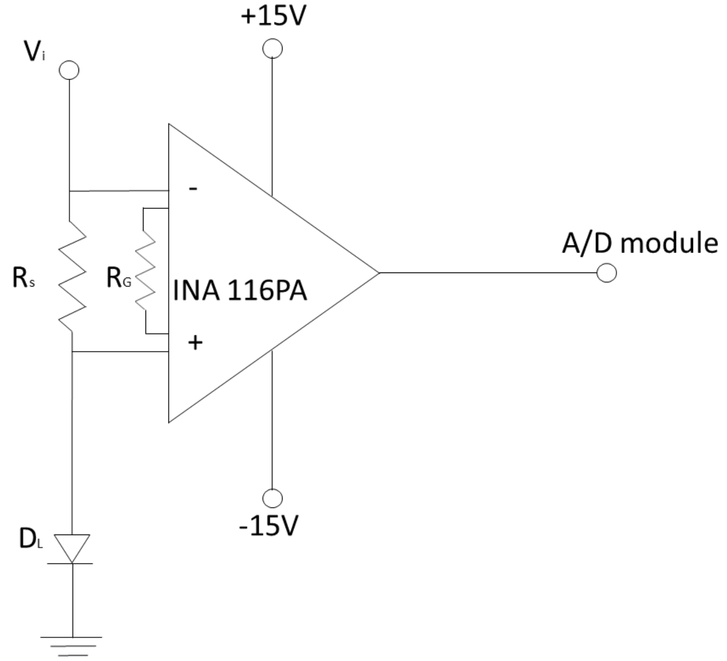


Figure 14: Case when measured device is nonlinear like diode

In order to realize the function, we need to build a programmable voltage source which can control the output voltage of the regulated power supply. In this project, the programmable voltage source is based on a conventional regulated power supply. Raspberry Pi is used as the control circuit. The quad-channel, serial-input 16-bit D/A converter DAC8534 from Texas Instruments® is used. This is a 16-pin DIP packaged D/A converter chip that uses +2.7V~+5.5V DC power supply to output analog voltage values. The DAC8534 is compatible with the SPI bus of Raspberry Pi's microprocessor. It uses its internal 24-bit serial-to-parallel shift register to sequentially write three 8-bit bytes. The control signal is used to pass the value to be converted through the Raspberry Pi's I/O port. It is sent to the D/A converter and converted to the corresponding analog voltage. The working flow of the programmable voltage source can be seen from Figure 15. At beginning the function will initialize the port, clock, D/A converter and regulated power supply, then the function will monitor input voltage of the measured device. If the measured input voltage is less than target input voltage, then Raspberry Pi will increase output voltage of the power supply; if the measured input voltage is greater than target input voltage, then Raspberry Pi will decrease output voltage of the power supply. Through this method we can ensure target measurement voltage is input to small current amplifier.

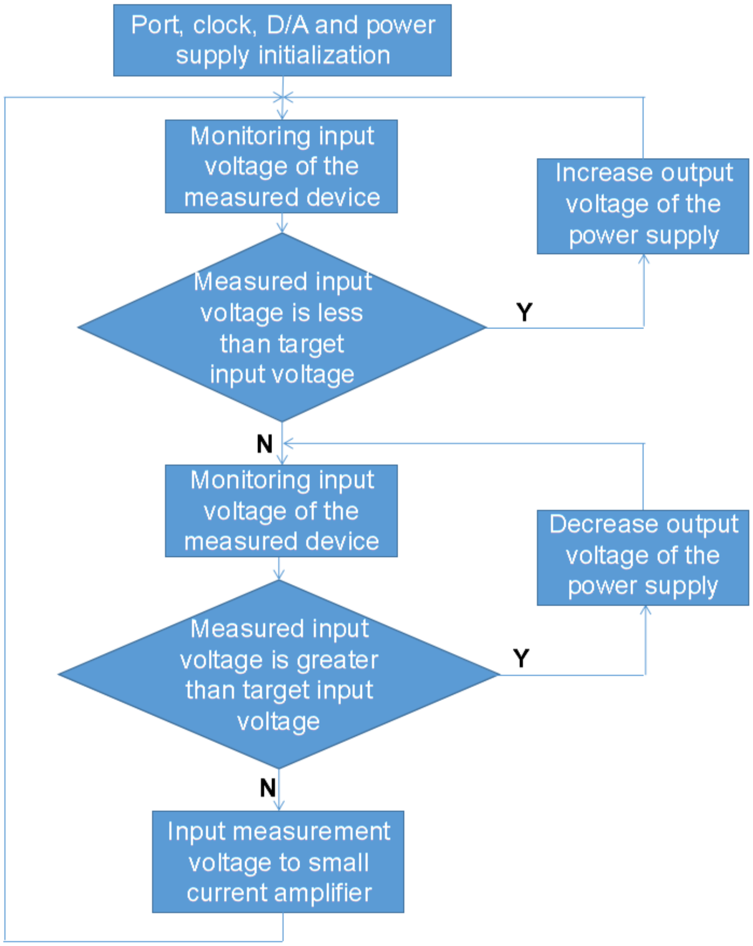


Figure 15: Principle diagram of voltage tracking function in current measurement

Actually, when increase or reduce the input voltage of the operational amplifier, the current flow through R_S will also change, which will change its voltage drop. So in this way we can not make the real input voltage of the measured device totally equal to the target value. The error between the target value and real input voltage should be no more than 0.0005V.

4 AMPLIFIER CONFIGURATION AND OPERATION RESULTS

In this Chapter we will evaluate the performance of the designed small current amplifier. Firstly, we will measure different standard resistor and compare its measuring error under different measuring range with current semiconductor parameter analyzer. Next, we will introduce the procedure of reducing measurement error of small current by ways of zeroing, reducing leakage current, taking the average and shielding. Then we will measure diode in single channel to test the automatic gain control function. Finally, we will measure triode and MOSFET to test multi-channel measuring function of the analyzer.

4.1 Measurement of Standard Resistance and Performance Comparison with Current Analyzer

In this section, in order to verify the measuring performance of the analyzer on double-ended linear devices such as resistance, we intend to measure different standard resistances and compare with the values measured by the existing analyzer.

We measured different standard resistances and compare with the values measured by the existing analyzer, we selected the standard resistance that grows from 100 Ω to 1 GΩ in ten-times relationship. We measured their I-V characteristics with our built analyzer and existing analyzer. The current analyzer we use in laboratory is Keithley 4200A-SCS/F from Tektronix®. It has 4 SMU, its maximum I-V measuring current is 100 mA; its minimum I-V measuring resolution is 0.1 fA and its maximum I-V measuring voltage is 200V [22]. We use the same method to import data into Excel and get the trend line equation, which can be seen from Figure 16. From the trend line function, we can get the resistance measured by two parameter analyzers and compare their difference.

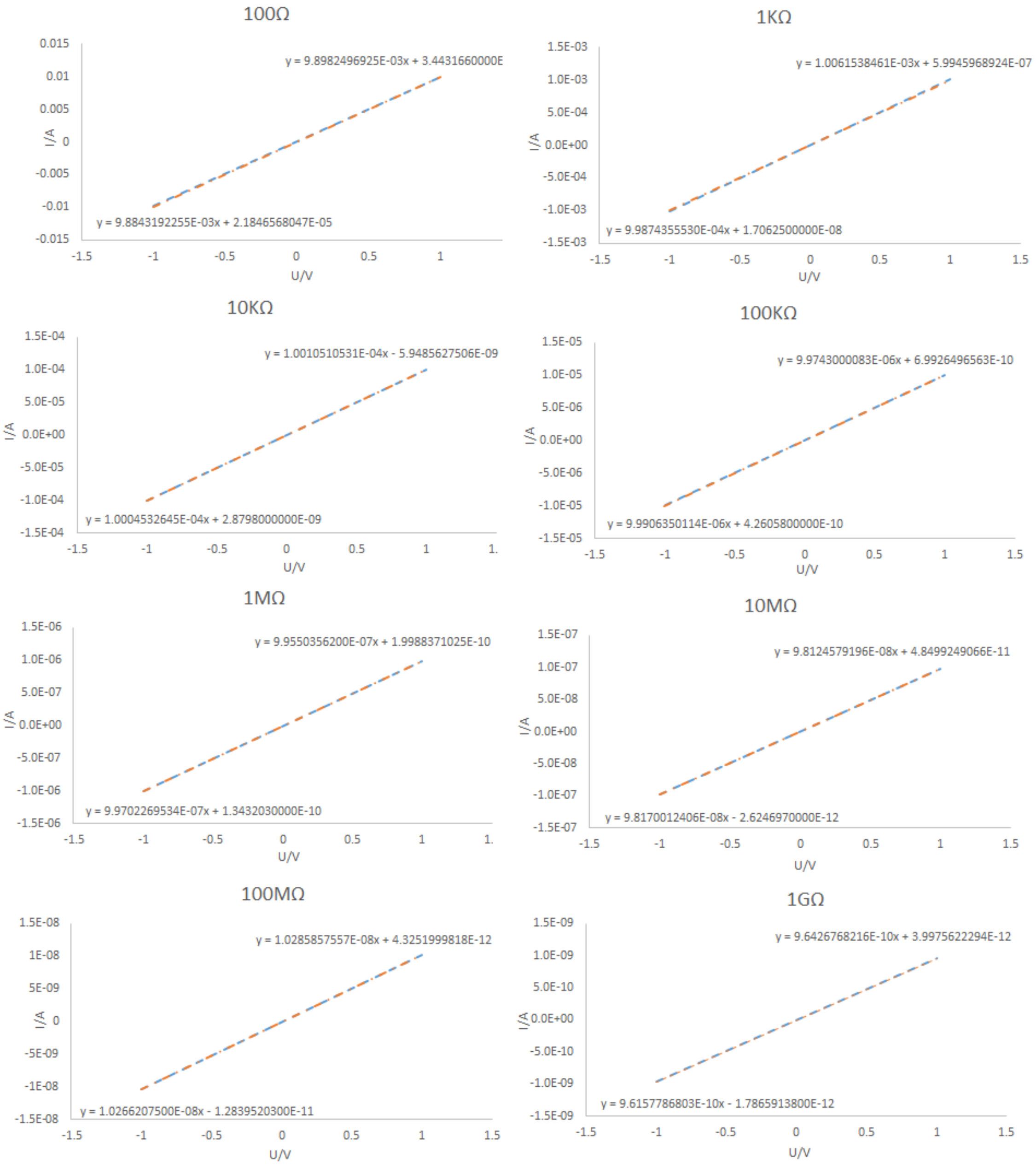


Figure 16: I-V characteristics of different standard resistance measured by two analyzers

From the curve we can see that both analyzers well reflect the linear characteristics of the resistance, and the curves measured by the two analyzers are almost identical.

In order to show the difference, we keep the slope parameter of the trend line equation to ten decimal places by scientific notation, then the resistance value is the reciprocal of the slope. We calculate the value of each standard resistance by these curves and compared the measured difference between two analyzers and the ratio of resistance difference to the measured resistance value, which can be seen from Table 3. We also plotted the ratio of resistance difference to the measured resistance value, which can be seen from Figure 17. We can see that the difference in resistance measured by the two analyzers increases as the measured resistance increases, but the ratio of the difference to the measured resistance value is always very low, no more than 1%, besides, the difference has both positive and negative numbers. In addition, the intercept parameter in the trend line equation actually reflects the bias current of the analyzer, this parameter is vital when measuring large resistors. We can see the intercept parameter values of the two curves are basically on the same order of magnitude, which indicates that the two analyzers have similar performance.

Measured resistance/Ω	100	1k	10k	100k	1M	10M	100M	1G
Resistance difference measured by two analyzers/Ω	0.138	0.0212931	-6.082	163.189	1523.7917	4648.426	-184367.209	-2896773.8
R_d/R_m	0.00138	0.0000212931	-0.0006082	0.00163189	0.001523792	0.000464843	-0.001843672	-0.002896774

Table 3: measured difference between two analyzers and the ratio of resistance difference to the measured resistance value

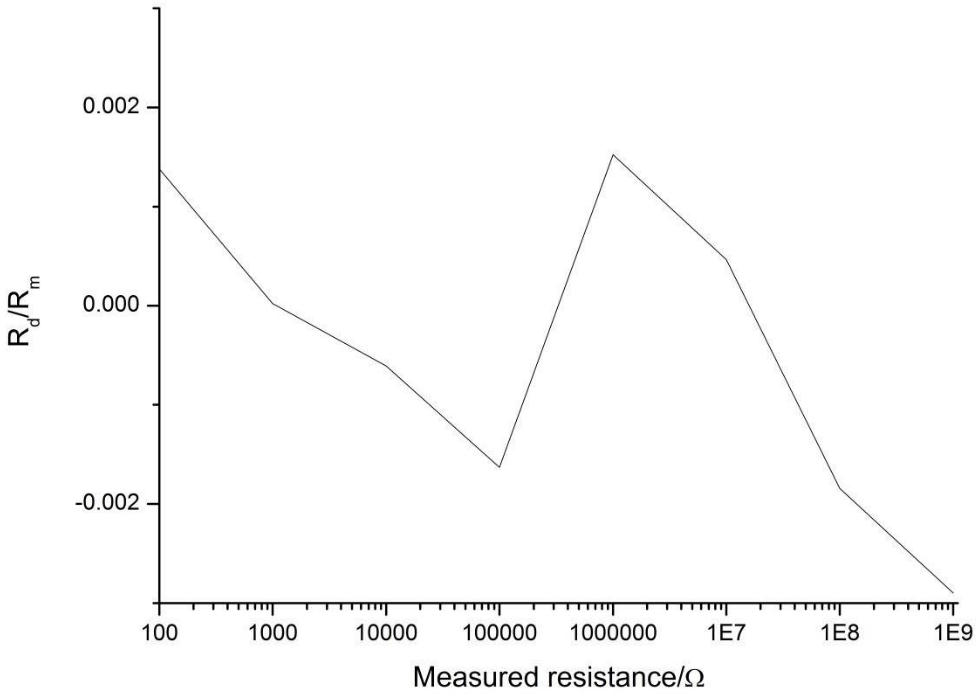


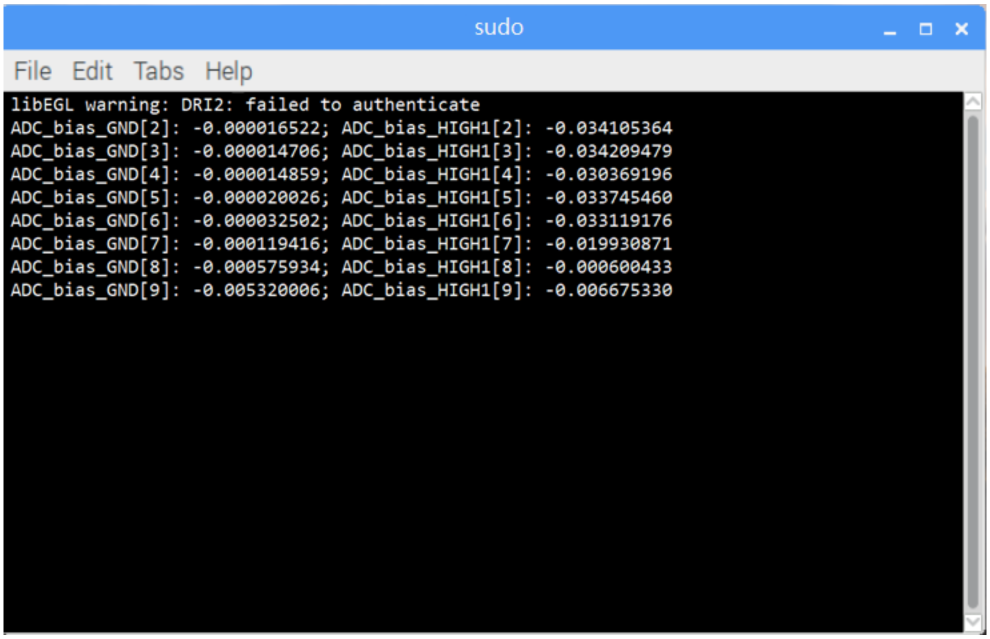
Figure 17: ratio of resistance difference to the measured resistance value

4.2 Methods Used to Reduce the Measurement Error of Small Current

In this section, the methods used to reduce the measurement error of small current will be presented. We tried to reduce the measurement error of small current by zeroing input bias current of ADC, reducing leakage current of the amplifier, taking the average to avoid random interference and shielding the analyzer and measured device.

4.2.1 Zeroing ADC's Input Bias Current

Since ADC consists of many JFET or CMOS amplifiers which have input leakage current, the small current signal is easily merged in the leakage current if we don't take actions to reduce it. In our analyzer we set up the function which can zero ADC's input bias current, we add "Zero_IMU" button in the user interface, user needs to push the button before each measurement, otherwise the bias current may be so large that interfere our measurement. The maximum DC leakage current of AD7606 is ±1 μA, but our measured current is in pA order of magnitude, so we need to reduce the leakage current of ADC by software. When the detected current is not too small, in this case R_S is from 1 Ω to 1 MΩ, we divide the ADC's leakage current by 50000; when the detected current is small, in this case R_S is 10 MΩ, we divide the ADC's leakage current by 100000. After zeroing, the results will be shown in the command window, which can be seen in Figure 18.



```
libEGL warning: DRI2: failed to authenticate
ADC_bias_GND[2]: -0.000016522; ADC_bias_HIGH1[2]: -0.034105364
ADC_bias_GND[3]: -0.000014706; ADC_bias_HIGH1[3]: -0.034209479
ADC_bias_GND[4]: -0.000014859; ADC_bias_HIGH1[4]: -0.030369196
ADC_bias_GND[5]: -0.000020026; ADC_bias_HIGH1[5]: -0.033745460
ADC_bias_GND[6]: -0.000032502; ADC_bias_HIGH1[6]: -0.033119176
ADC_bias_GND[7]: -0.000119416; ADC_bias_HIGH1[7]: -0.019930871
ADC_bias_GND[8]: -0.000575934; ADC_bias_HIGH1[8]: -0.000600433
ADC_bias_GND[9]: -0.005320006; ADC_bias_HIGH1[9]: -0.006675330
```

Figure 18: Pop-up command window after zeroing

4.2.2 Reduce Leakage Current of the Amplifier

Leakage current has a very important impact on performance of the current amplifier; it mainly comes from operational amplifier, relays and PCB board. In our project, we did a lot on these three aspects so that to reduce the leakage current of small current amplifier.

Firstly, the ADC we select has very low leakage current. The maximum DC leakage current of AD7606 is ±1 μA [12]. Besides, we tried several delays from CRSS1A05 to MS05-1A87-75DHR. When we use CRSS1A05, we find the leakage current of some delays are quite large, the leakage current can be up to about 3 nA, which can be seen in Figure 19, this is not acceptable. After that, we look up the datasheet of CRSS1A05, its minimum insulation resistance is 100MΩ [23], this leakage current is within the limit. But in order to guarantee the performance of small current amplifier, we should find a relay which has very small leakage current. We finally use MS05-1A87-75DHR produced by Standex Electronics®, its minimum insulation resistance is 1 TΩ [24], which means its leakage current will not exceed 1pA, so it satisfies our requirement.

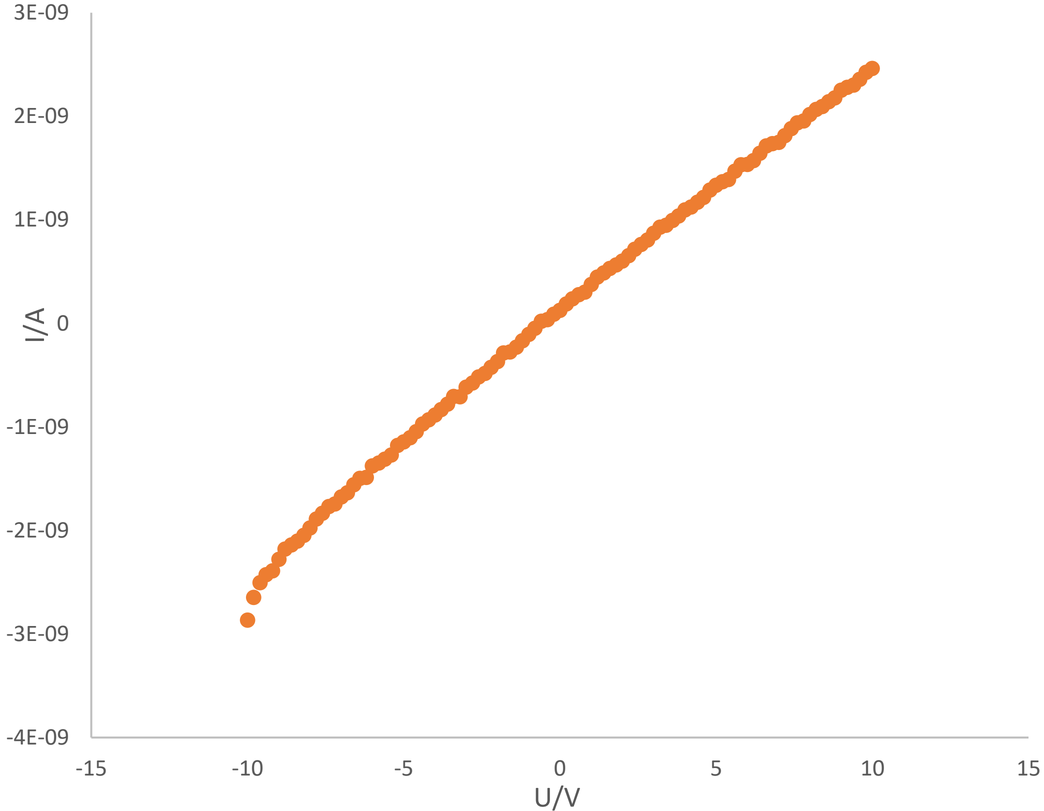


Figure 19: Leakage current of CRSS1A05

The PCB board we use also has leakage current. Printed Circuit Board (PCB) is the support for circuit components and devices in electronic products. It provides electrical connections between circuit components and devices. In our project, we use conventional FR-4 substrate named S1141 produced by Shengyi Technology®, its surface resistivity is 5.4×10^7 MΩ, its volume resistivity is 5.2×10^8 MΩ-cm [25], the substrate's thickness is 1.6mm, which means its surface leakage current is only about 19 fA, its inside leakage current is only about 12 fA, so it fully meets our requirements.

With the quick development of electronic technology, the density of components and wires of PCBs is getting higher and higher, and interference between components of different purpose and wires of different level is becoming more and more serious [26]. Although the PCB substrate we use has very low leakage current, in wiring process, we still need to follow some principle to reduce the leakage current of PCB board.

- ports and wiring connected with IN+ should be as far as possible between ports and wiring connected with IN- so that to avoid leakage current between IN+ and IN-.
- leakage current between the measurement loop and the control loop of the relay also needs to be considered, the wiring of the measuring circuit should be as far as possible from the port and wiring of the control circuit.
- all ports and wiring connected with IN+ and IN- should be as far as possible from 3.3V channel selection voltage input.
- all ports and wiring connected with IN+ and IN- should be as far as possible from 5V and ±15V voltage input.
- PCB size selection should be reasonable. When the PCB size is too large, the printed lines are long, the impedance is increased, the noise resistance

decreases, and the cost is also increased; if the size is too small, the heat dissipation is not good, and the adjacent lines are easily disturbed.

- The position of each functional circuit unit is arranged according to the flow of the circuit, so that the layout facilitates signal flow and the signal is kept in the same direction as far as possible. You can choose to layout around the core component of each functional circuit. Components should be evenly, neatly and compactly arranged on the PCB. The connections between the components should be as short as possible.
- Since circuits often need to operate in high frequency environments, the distribution parameters between components need to be considered. The components should be arranged in parallel as much as possible. In this way, not only the layout is beautiful, the welding is convenient, but also easy to mass production.

According to these principles, we have optimized the wiring of PCB board, which can be seen in Figure 20. The black wire marks the optimization we have made: ① to ⑤ are optimizations based on the first principle; ⑥ is optimization based on the second principle; ⑦ is optimization based on the third principle; ⑧ is optimization based on the forth principle. Besides, based on the last three principles, we can see that all components and devices are layout around the instrumentation amplifier INA 116PA, and all relays are parallel to each other. Lastly, all components are evenly and compactly arranged on the PCB and the size of PCB board is also convenient for us to arrange the wiring reasonably.

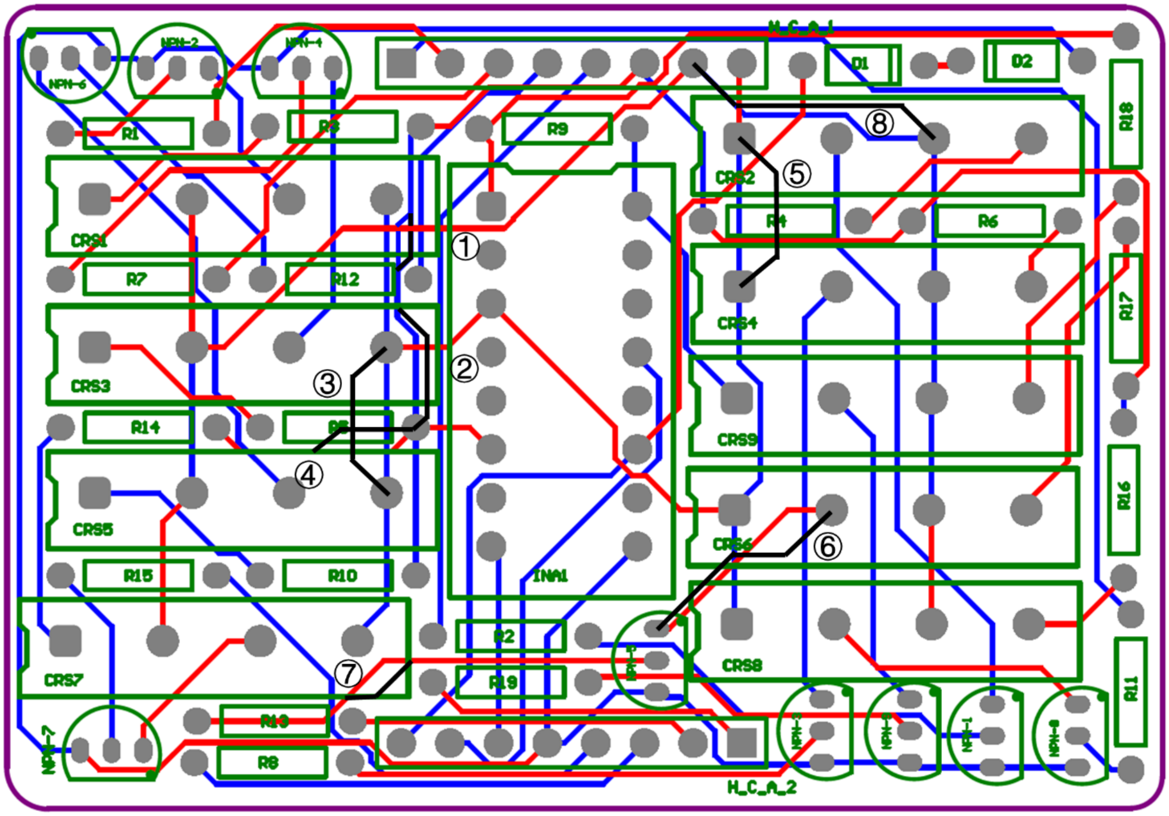


Figure 20: Optimized wiring of PCB board

4.2.3 Taking Average to Avoid Random Error

In the process of using current semiconductor parameter analyzer, We find that sometimes the measurement curve has a severe oscillation, this is due to the wet measurement environment or contaminant on PCB board, electrochemical reactions will occur between contaminant and humid air, which forms a weak "battery" attached to the board conductor. For example, oil, salt, fingerprint or some other contaminant can generate interference currents close to several nA between board conductors. Therefore, we should choose insulating materials which do not absorb water and minimize the environmental humidity to reduce the measurement error. Besides, all insulators in the measurement circuit must be kept clean and free of dust and impurities [27]. However, we can not guarantee the absolute suitable environmental humidity and clean PCB board in actual use. So we take the method of measuring several times then take the average to avoid the interference of random error on small current amplifier.

In the source code, we define a variable called N_Average, which can be used to control the number of averaging. The larger the N_Average, the more times to measure and take the average, and the measured curve is less susceptible to noise interference theoretically. We set N_Average as 100, 1000, 10000 respectively and measured the I-V characteristic curves of the analyzer under no-load state, which can be seen in Figure 21. We can see that when N_Average is more than 1000, the measured curve is much smoother; but when N_Average is only 100, the curve is severely oscillated, which indicate that averaging is essential for measurement.

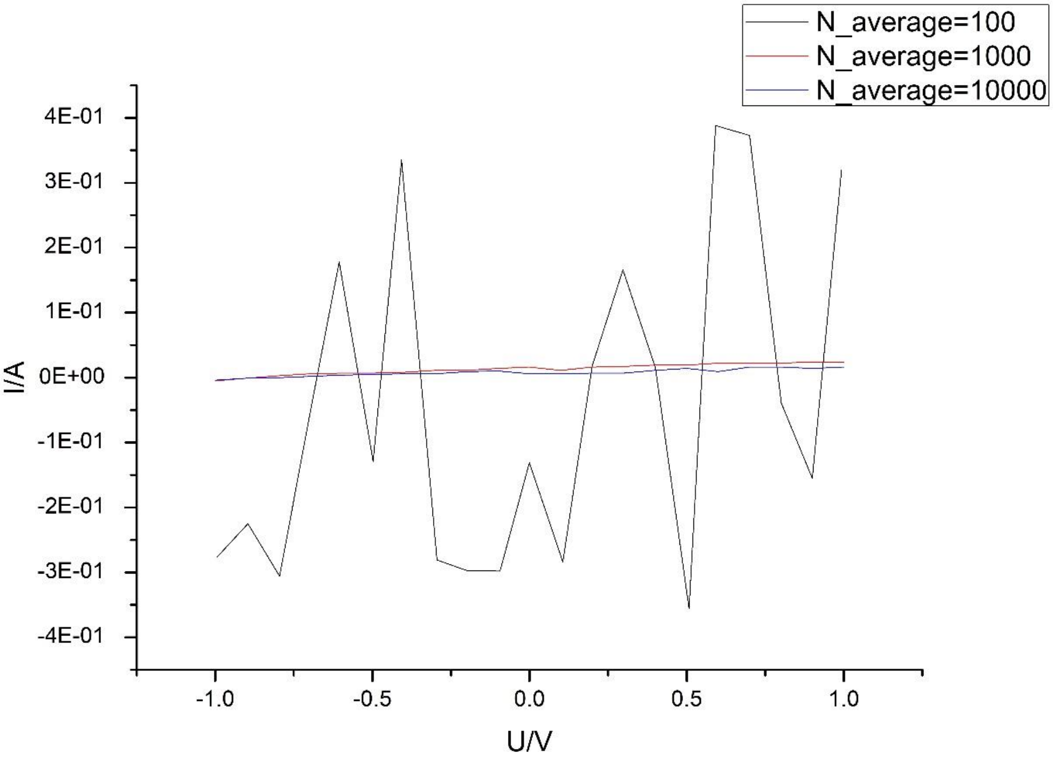


Figure 21: Comparison of measurement results under different average times

4.2.4 Shielding

After concentrating on zeroing, reducing leakage current and averaging, the last thing we need to consider is shielding. In the use of small current amplifier, it is often subject to high frequency interference caused by external signals, which is commonly referred to as "Electromagnetic Interference (EMI)". EMI includes conducted interference (low frequency), radiated interference (high frequency), electrostatic discharge and interference caused by lightning. Among them, conducted interference and radiated interference are the two main types. Conducted interference refers to the coupling (interference) of signals on one electrical network to another through a conductive medium. Radiated interference refers to the interference source coupling (interfering) its signal to another electrical network through space. Conditions that generate EMI include sudden changes in voltage or current, radiating antennas, or conductive conductors. Today, when human beings enter the information society, electromagnetic waves have been widely used as information resources in IT products in the wide frequency range of 0~400GHz, and the EMI that comes with them is radiated or transmitted to the running electronic device or system and the surrounding environment from low frequency to microwave segment, which brings more and more serious damage to the device or system. The propagation of the radiated electromagnetic field in space (such as electromagnetic waves) is due to the interaction of the electric field and the magnetic field, and its propagation velocity is equal to the speed of light. The work of radio broadcasting and communication equipment often radiates electromagnetic waves with high power. In addition to professional radio transmitters, spark plugs, arcs, brush motors, high-power contactors, frequency converters, other circuits that operate at high frequencies, and hyperthermia equipment in medicine emit electromagnetic waves. Besides, any wire carrying high-frequency current in the detection device will also emit electromagnetic waves to the surroundings.

When an unshielded amplifier is exposed to tens or hundreds of "megahertz" RF radiation, the input stage of the amplifier may be asymmetrically rectified, resulting in a dc offset that is more pronounced after amplification, plus the gain of the amplifier, finally even reach the upper limit of its output or part of the external circuit [28]. Besides, wires, especially long wires, such as signal input and output lines, control lines, power lines, etc., can receive electromagnetic waves in an electromagnetic field to induce noise voltage. As a source of noise, these wires can radiate electromagnetic waves. It can be seen that in addition to external electromagnetic interference, there are mutual nuisances inside the electronic device or system, such as crosstalk interference (referred to as noise interference introduced by the coupling of distributed capacitance when the line and the line are close to each other).

Because the conductor has a reflection and absorption effect on electromagnetic radiation noise, it is necessary to shield the small current amplifier and even the whole analyzer. In our project, we shielded both the measured device and analyzer, Since the shielding effect of high frequency (1 MHz and above) steel is the best when the shielding body is the same shape and the wall thickness is the same, we use 304 stainless steel as the shielding material. Besides, in practical shielding, with few exceptions, there are inevitably many holes and gaps in the shield. These holes and gaps create additional channels for the penetration of the field. Therefore, the shielding effectiveness is reduced. However, it is still possible to find out the law so that the reduced shielding effectiveness is as small as possible.

- In general, replacing a large hole with several small holes having the same total area will weaken the field penetrating into the space protection zone. When a certain condition is met, when one large hole is replaced by several small holes with same total area, the field penetrating into the space protection zone will be weakened to $1/\sqrt{n}$ of the original field.
- The wall thickness does not actually affect the field through the hole. However, placing a sleeve on the hole greatly reduces the field through the hole. Dividing a large hole into several small holes and deepening each small hole with a sleeve at the same time can significantly reduce the field strength through the hole [29].

Based on above principles, we designed separate holes for each signal port on the shield, and the sleeve of the signal port is long enough to extend the hole, which can be seen from Figure 22. After shielding, the leakage current of the amplifier reduced a lot, which can be seen in Figure 23. Two dashed lines are the result of taking the logarithm of the measured leakage current to reflect the rising and falling trend of the leakage current, which can be ignored here. From two solid lines, we can see before shielding, the leakage current from -10 V to 10 V is about -3×10^{-11} A to 2.5×10^{-11} A; after shielding, the leakage current from -10 V to 10 V is about -1×10^{-11} A to 1.375×10^{-11} A, drops by about two thirds, which verified that shielding plays an important role in improving performance of the small current amplifier.

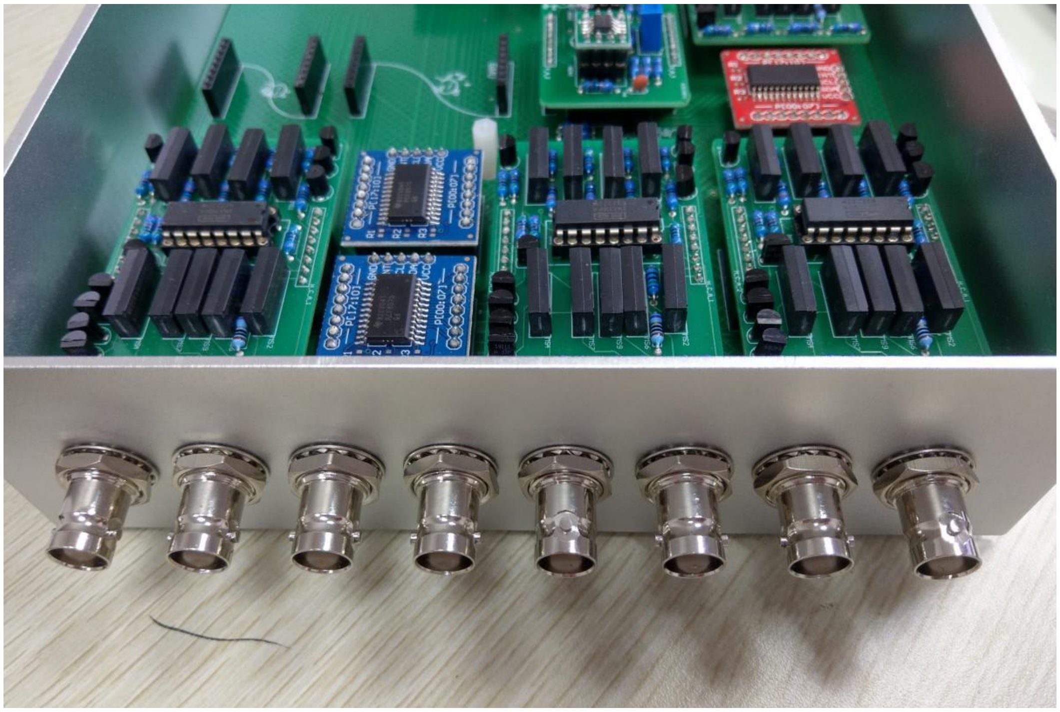
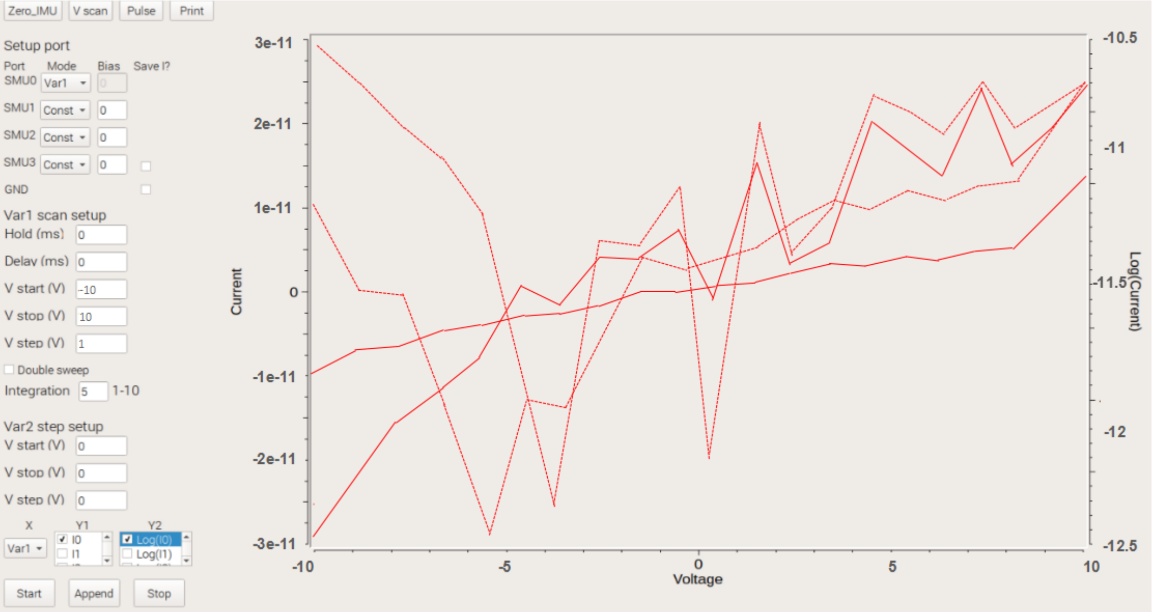


Figure 22. Shielding of the current amplifier



Setup port

Port	Mode	Bias	Save I?
SMU0	Var1	0	
SMU1	Const	0	
SMU2	Const	0	
SMU3	Const	0	☐
GND			☐

Var1 scan setup
Hold (ms) 0
Delay (ms) 0
V start (V) -10
V stop (V) 10
V step (V) 1
☐ Double sweep
Integration 5 1-10

Var2 step setup
V start (V) 0
V stop (V) 0
V step (V) 0

X: Var1
Y1: ☑ I0 ☐ I1
Y2: ☑ Log(I0) ☐ Log(I1)

Figure 23: Leakage current of the amplifier before and after shielding

4.3 Measuring Diode (Single Channel) and Automatic Range Switching Function

In the first section of this Chapter, we verified the performance of the current amplifier under various ranges by measuring the standard resistance in each range and comparing the performance with the existing analyzer. In this section we will verify the single-channel range auto-switching function of the current amplifier by measuring nonlinear devices such as diodes.

The I-V characteristics of diode includes forward characteristics, reverse characteristics and reverse breakdown characteristics. Which can be seen in Figure 24. In this section we only discuss forward characteristics and reverse characteristics.

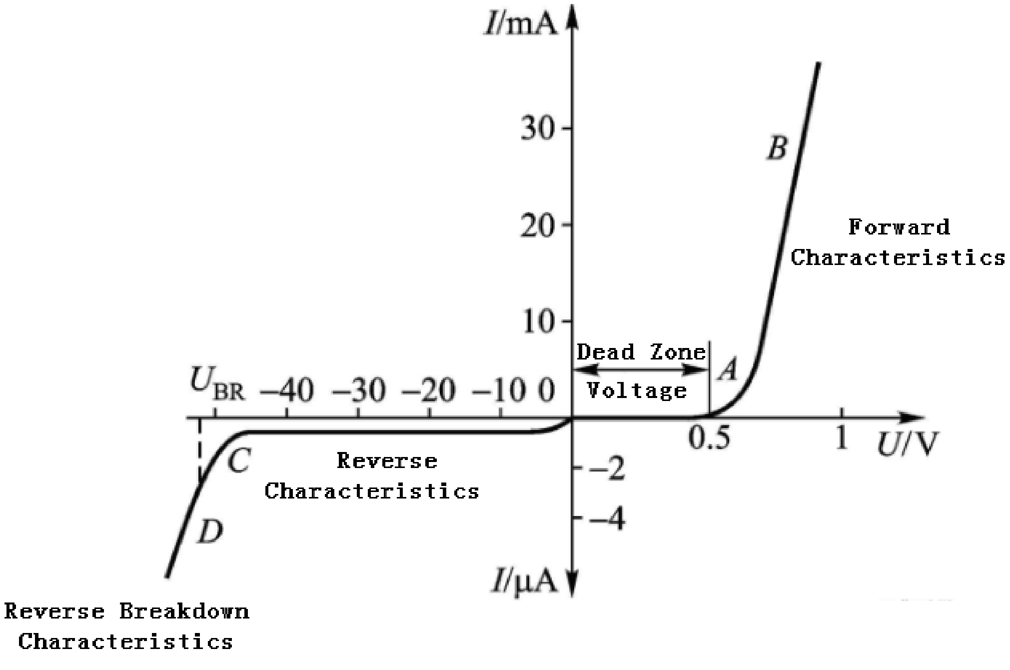


Figure 24: I-V characteristics of diode

The first quadrant of the I-V characteristics curve of the diode is called forward characteristic, which indicates the operation of the diode when the forward voltage is applied. At the beginning of the forward characteristic, since the forward voltage is small, the external electric field is not enough to overcome the hindrance of the internal electric field to the majority carriers, and the forward current is almost zero. When the forward voltage exceeds a certain value, the internal electric field is greatly weakened, the forward current is rapidly increased, and the diode is turned on. This area is called the forward conduction region. Once the diode is turned on, as long as the forward voltage changes slightly, the forward current changes greatly, and the forward characteristic curve of the diode is steep, the forward current density increases exponentially with voltage [30]. This region is called the I-V characteristics curve of the forward diode.

The third quadrant of the I-V characteristics curve of the diode is called the reverse characteristic, which indicates the operation of the diode when the reverse voltage is applied. In a certain reverse voltage range, the reverse current is small and does not change much. This area is called the reverse cut-off area. This is because the reverse current is formed by the drift motion of minority carriers; at a certain temperature, the number of minority carriers is basically constant, so the reverse current is basically constant, regardless of the magnitude of the reverse voltage, so it is usually called reverse saturation current [31].

After discussing about the I-V characteristics of diode, we then introduce the input I-V characteristics of triode, which means when U_{CE} is stable, the relationship between input voltage U_{BE} and input current I_B. The relationship can be seen in Figure 25, we can see that the input characteristics of triode is almost the same as the I-V characteristics of diode. However, the curve shifts slightly to the right as the U_{CE} increases. Based on above discussion, we can indirectly characterize the I-V characteristics of the diode by measuring the input I-V characteristics of the triode with a stable U_{CE}.

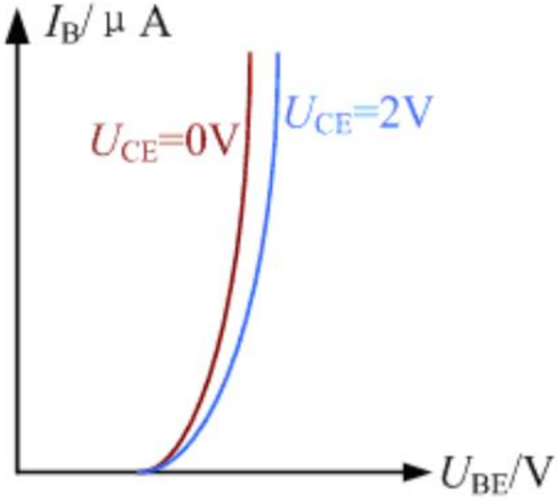
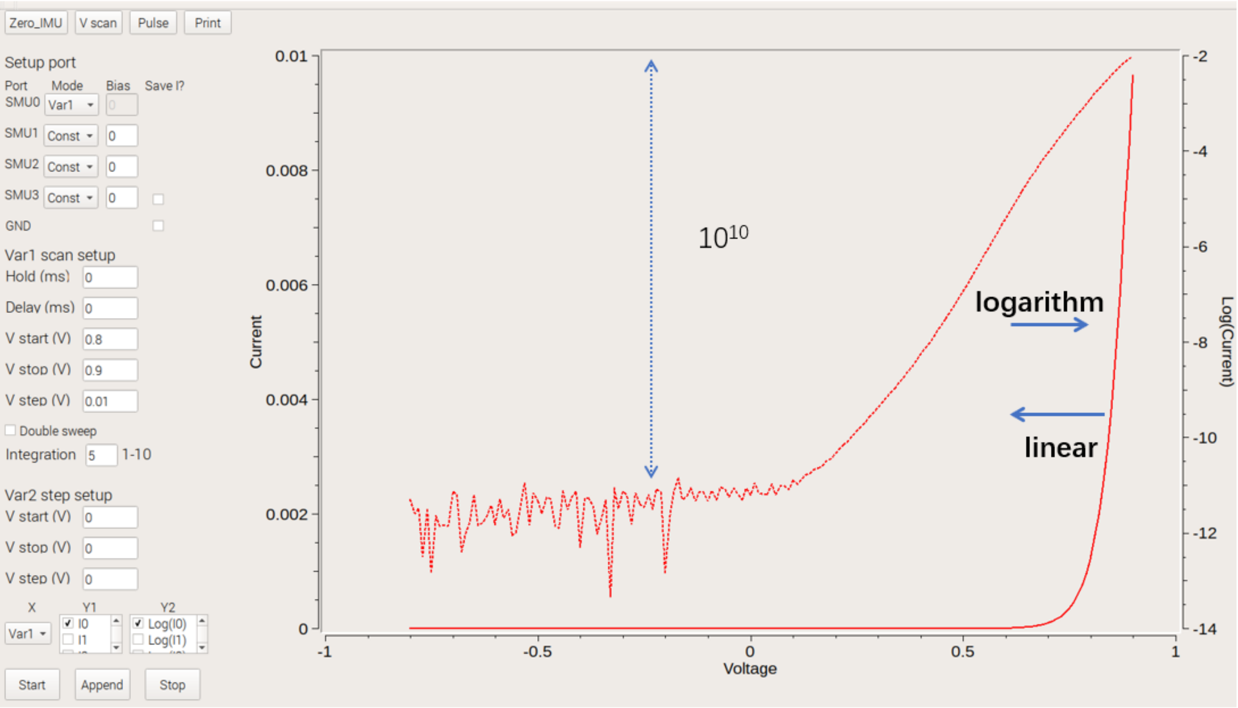


Figure 25: Input I-V characteristics of triode

Since in forward conduction region, any slight voltage change will cause a sharp change in current, this requires the amplifier to have the ability to automatically switch the range. We measured the I-V characteristics of the base and emitter of the S9018 diode with the built-in amplifier. The result can be seen in Figure 26. The ordinate axis on the left is the measured current value, the coordinate axis on the right is the logarithm of the current. From the right axis we can visually see the magnitude change of the current, current amplifier can measure current from 10^{-12} A to 10^{-2} A, crossed ten orders of magnitude, which verifies that range auto-switching function works very well. Besides, since in forward conduction region, the forward current density increases exponentially with voltage, in the measurement results, we can see that the logarithm of the current increases linearly with the voltage.



Setup port

Port Mode Bias Save I?

SMU0 Var1

SMU1 Const 0

SMU2 Const 0

SMU3 Const 0 ☐

GND ☐

Var1 scan setup

Hold (ms) 0

Delay (ms) 0

V start (V) 0.8

V stop (V) 0.9

V step (V) 0.01

☐ Double sweep

Integration 5 1-10

Var2 step setup

V start (V) 0

V stop (V) 0

V step (V) 0

X: Var1

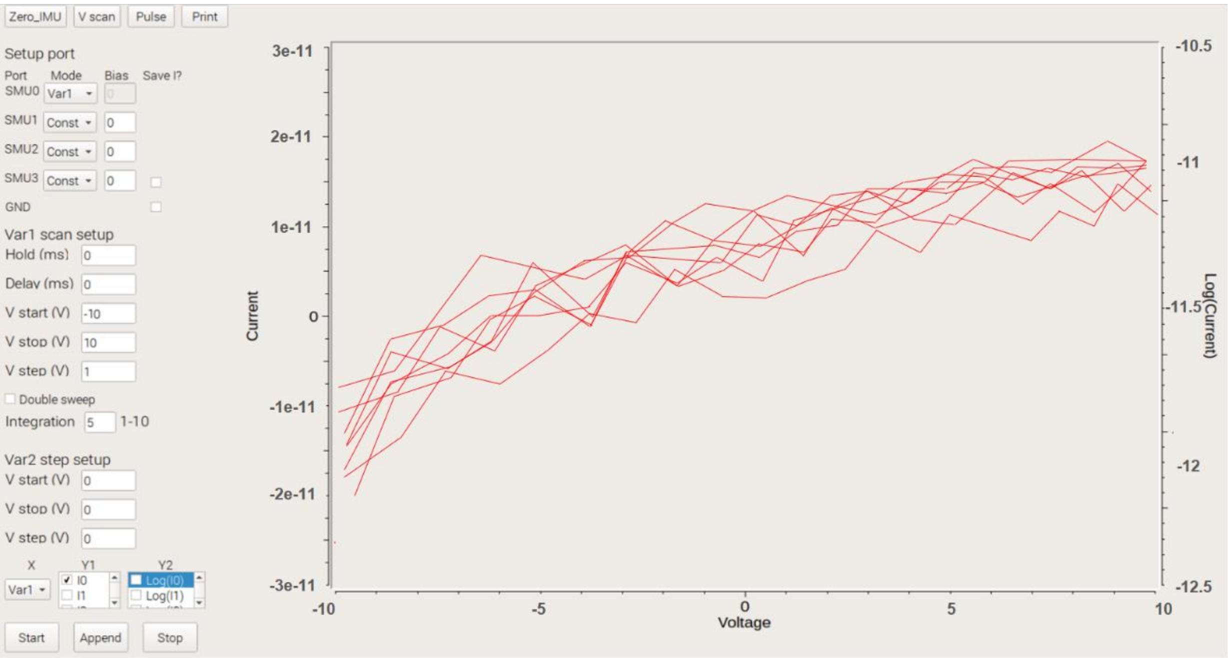
Y1: ☑ I0 ☐ I1

Y2: ☑ Log(I0) ☐ Log(I1)

Figure 26: Measuring S9018 (e-b) and automatic range switching function

4.4 Measuring Triode and MOSFET (Multi-channel)

For multi-channel small current amplifiers, the stable linear gain and the low difference of each channel gain are the basic requirements to ensure the true signal of the overall measurement system. So before measurement, We need to ensure that the performance indicators of the four current amplifying modules are basically the same. Through the above methods to reduce the measurement error of small current, finally, we found that the performance of the instrumentation amplifier INA116 determines the performance of the entire current amplifying module. We purchased a batch of INA 116PA modules and selected 4 of them as the instrumentation amplifiers with the best and closest performance for current amplifying modules. The testing results can be seen from Figure 27. We measured the leakage current twice for each current amplifying module where INA 116 is inserted. Due to the large number of measurements, we turned off the function of taking logarithm to avoid affecting the observation. It can be seen that the leakage current of the four current amplifying modules installed with INA 116 is very low and close to each other, which ensures the consistency and authenticity of the data in multi-channel measurement.



Setup port

Port	Mode	Bias	Save I?
SMU0	Var1	0	
SMU1	Const	0	
SMU2	Const	0	
SMU3	Const	0	☐
GND			☐

Var1 scan setup
Hold (ms) 0
Delay (ms) 0
V start (V) -10
V stop (V) 10
V step (V) 1
☐ Double sweep
Integration 5 1-10

Var2 step setup
V start (V) 0
V stop (V) 0
V step (V) 0

X Var1
Y1 ☑ I0 ☐ I1
Y2 ☐ Log(I0) ☐ Log(I1)

Figure 27: Comparison of leakage current of current amplifying modules with four different INA 116

Since in above discussion, we have introduced the input characteristics curve of triode. In this section, we will only introduce the output characteristics of triode. The output characteristics curve is the relationship between the output loop voltage U_{CE} and the output current I_C when the input current I_B is constant, which can be seen in Figure 28, it can be divided into three areas: cutoff region, saturation region, linear region.

- **Cutoff region** is the region pointed by A in Figure 28, this is the area where $I_B \leqslant 0$. At this time, the U_{BE} applied to emitter is not enough to overcome its dead zone voltage, and even the emitter is in the reverse bias state ($U_{BE} < 0$, so the formed I_C (or I_E) is small, only a very small penetration current I_{CEO}).

- **Saturation region** is the region pointed by C in Figure 28. When $U_{BE} > 0$ (the emitter is in positive bias) and overcome the dead zone voltage of the emitter, the triode will exit the cutoff region and I_B begins to appear. If $U_{CE} < U_{BE}$, then the collector junction is in a positively biased state, which is not conducive to the collection of electrons in the base region, so it basically does not change with the base current at this time. This phenomenon is called saturation. In the saturation region, the transistor loses its amplification, and the relationship between I_C and I_B is not β times. When the U_{CE} gradually rises until the beginning of the reverse bias ($U_{CE} > U_{BE}$), I_C will show rapid growth as U_{CE} rises, and finally break out of saturation and enter the linear region.
- **Linear region** is the region pointed by B in Figure 28. When I_B is constant, the number of electrons diffusing from the emitter to the base is generally constant. After U_{CE} exceeds a certain value (about 1 V), most of these electrons have been collected by the collector to form I_C. When U_{BE} continues to increase, I_C will not increase significantly, and it has a constant current characteristic. Only when I_B increases, the corresponding I_C also increases, and it increases much more than I_B. The current amplification of the triode is reflected here [32].

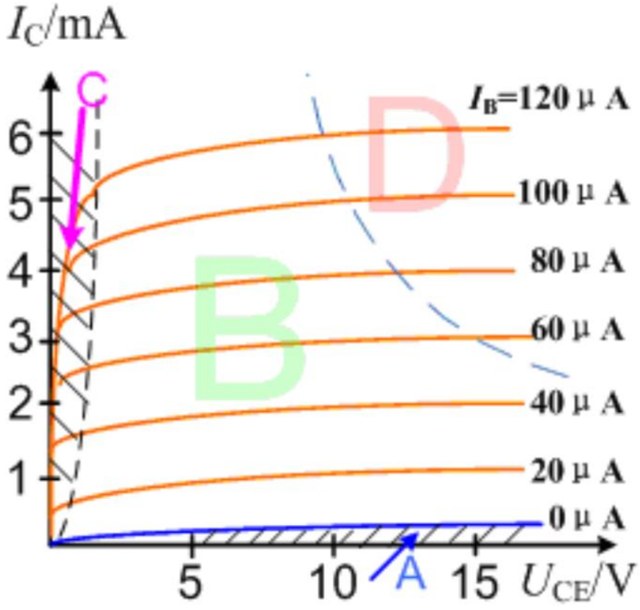


Figure 28: Output I-V characteristics curve of triode

Then we measured the I_B-V_{BE} characteristics of S9018 by our analyzer and existing analyzer, the testing results can be seen from Figure 29, the black hollow points indicate the I_B-V_{BE} characteristics measured by existing analyzer; the red solid line shows the I_B-V_{BE} characteristics measured by our analyzer, we can see that two curves are basically coincident. In order to analyze the similarity of the two curves, we plotted the relationship between the current measured by two analyzers at the same input voltage, which can be seen in Figure 30. The black solid points plot the relationship between two measured curves; the blue line is the linear fit of the curve; the red solid line represents the function of y=x, which can be used to compare with the linear fit line of the measurement results. We can see the intercept of linear fit line is very close to 0 and the slope of the linear fit line is almost 1. Besides, the R-square index of the curve is 0.99994, which is very close to 1, this indicates that curves measured by two analyzers are strong correlated.

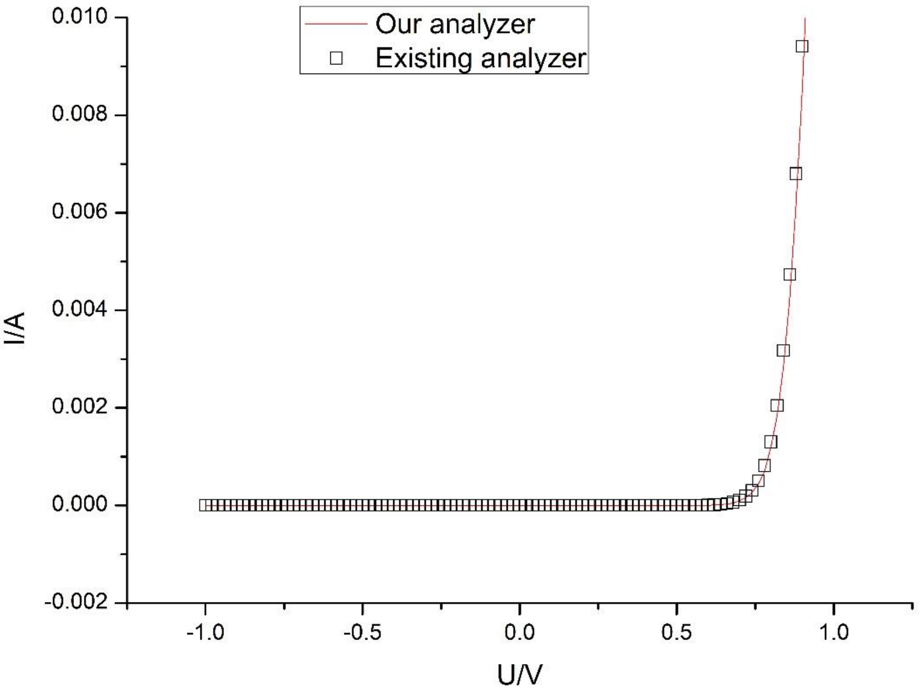


Figure 29: I_B-V_{BE} characteristics of S9018 measured by our analyzer and existing analyzer

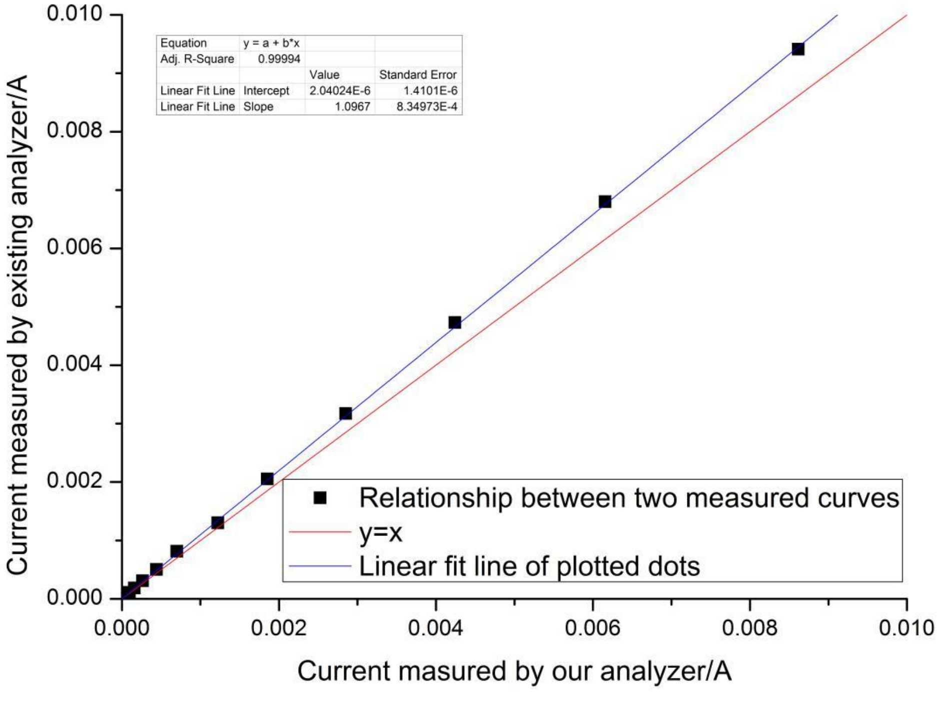


Figure 30: Relationship between two measured curves (S9018 e-b)

We also analyzed the relationship between error rate and measured current, which can be seen from Figure 31. We can see when the measured current is larger than 10 pA, the error rate is basically zero. Therefore, our analyzer has similar performance to the existing analyzer.

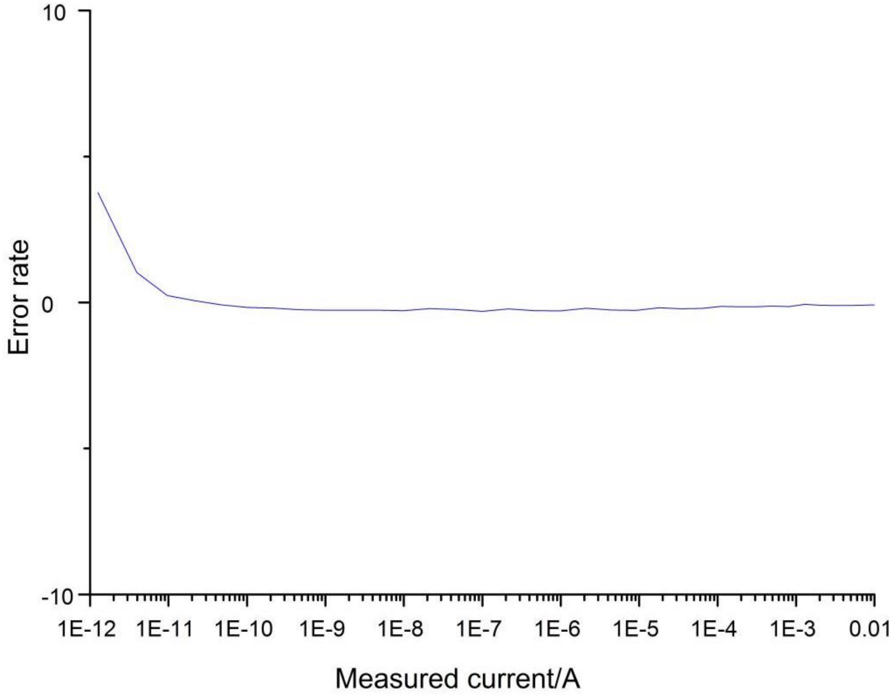


Figure 31: Relationship between error rate and measured current (S9018 e-b)

Then we measured the transfer characteristics of S9018 by our analyzer and existing analyzer, the testing results can be seen from Figure 32. The solid and dash line indicates the curve and its logarithm measured by our analyzer; the hollow points indicate the curves measured by existing analyzer, we can see the curves measured by two analyzers are almost identical. In order to analyze the similarity of the curves, we plotted the relationship between the current measured by two analyzers at the same input voltage, which can be seen in Figure 33. The black solid points plot the relationship between two measured I_B; the blue solid points plot the relationship between two measured I_E; the red line represents the function of y=x, which can be used to compare with the linear fit line of the measurement results. We can see the intercept of linear fit lines is very close to 0 and the slope of the linear fit lines is almost 1. Besides, the R-square index of the curves are 0.97252 and 0.99233 respectivel, which are very close to 1, this indicates that curves measured by two analyzers are strong correlated. We also analyzed the relationship between error rate and measured current, which can be seen from black dash line and red dash line. We can see that the error rate is always at a low level, not exceeding -0.3 nor 0.2. Therefore, our analyzer has similar performance to the existing analyzer.

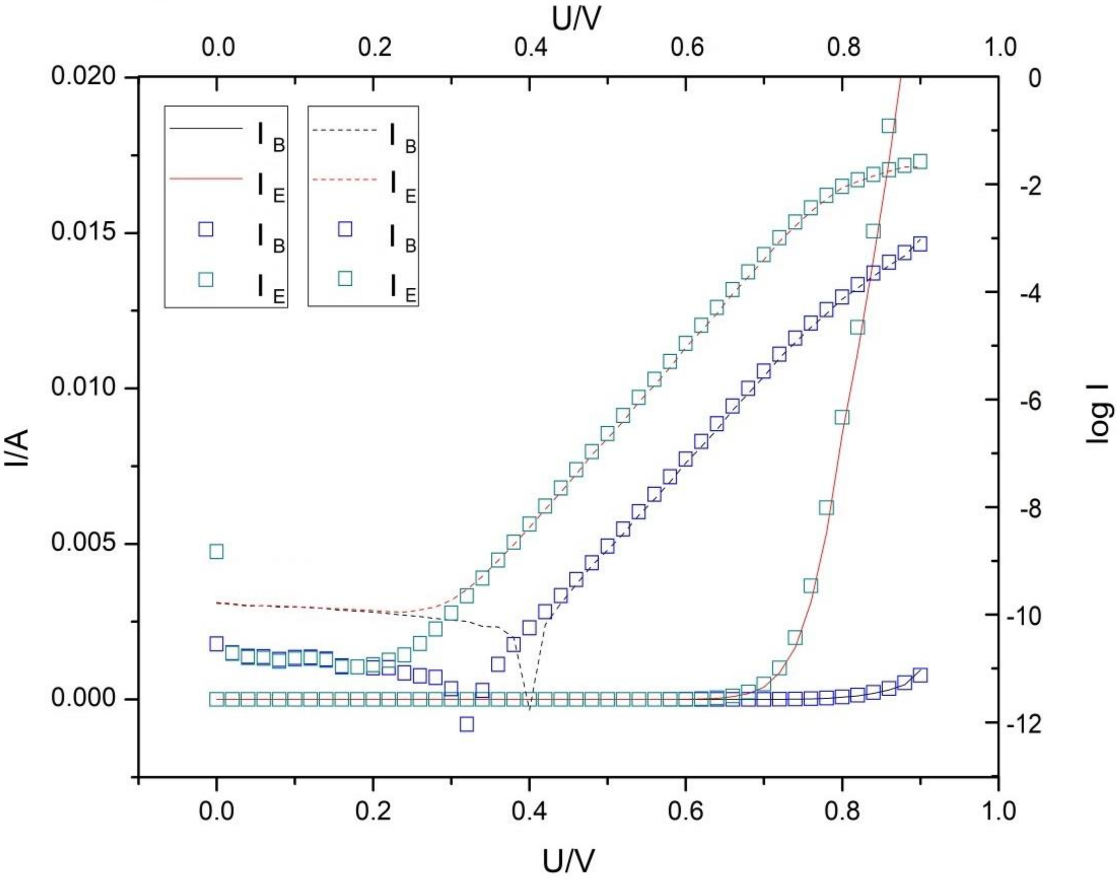
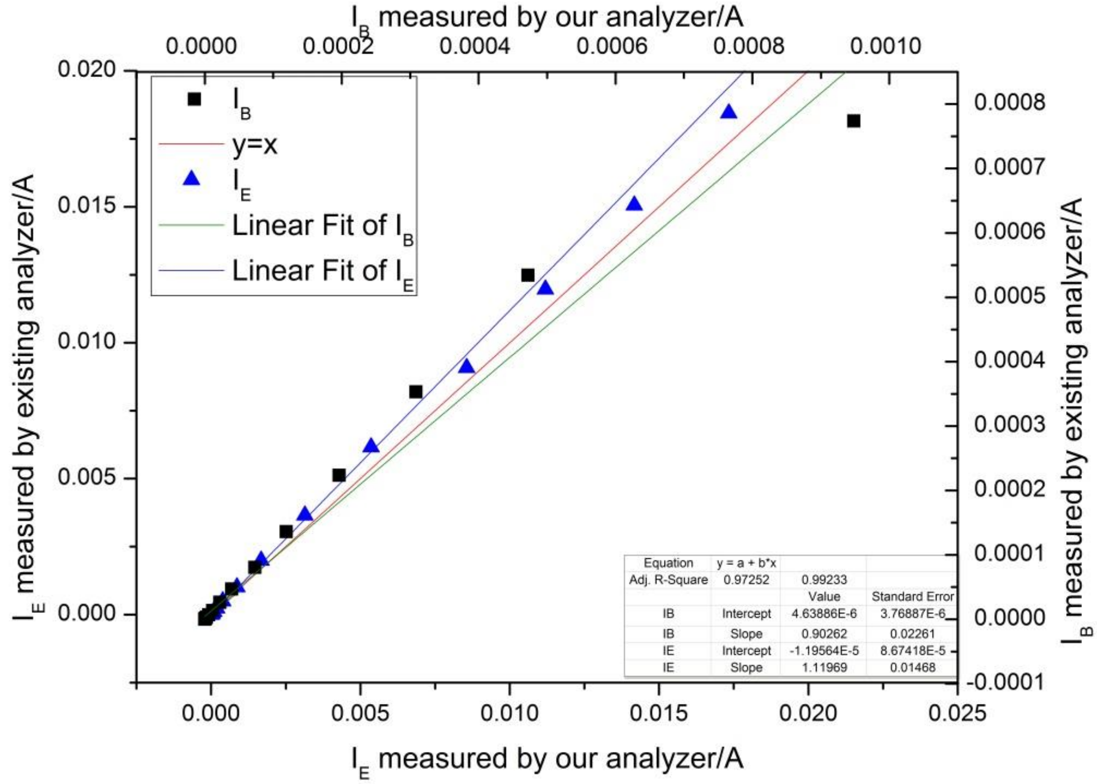


Figure 32: Transfer characteristics of S9018 measured by our analyzer and existing analyzer



Equation	y = a + b*x		
Adj. R-Square	0.97252	0.99233	
		Value	Standard Error
IB	Intercept	4.63886E-6	3.76887E-6
IB	Slope	0.90262	0.02261
IE	Intercept	-1.19564E-5	8.67418E-5
IE	Slope	1.11969	0.01468

Figure 33: Relationship between measured curves (S9018-transfer)

MOSFETs are tri-terminal, unipolar, voltage-controlled, high input impedance devices which form an integral part of vast variety of electronic circuits. These devices can be classified into two types viz., depletion-type and enhancement-type, depending on whether they possess a channel in their default state or no, respectively. Further, each of them can be either p-channel or n-channel devices as they can have their conduction current due to holes or electrons respectively. However, inspite of their structural difference, all of them are seen to work on a common basic principle. This further implies that all of them exhibit almost similar characteristic curves, but for differing voltage values.

In general, any MOSFET is seen to exhibit three operating regions viz.,

- **Cutoff region** is a region in which the MOSFET will be OFF as there will be no current flow through it. In this region, MOSFET behaves like an open switch and is thus used when they are required to function as electronic switches.
- **Ohmic or linear region** is a region where in the current I_{DS} increases with an increase in the value of V_{DS}. When MOSFETs are made to operate in this region, they can be used as amplifiers.
- In **Saturation region**, the MOSFETs have their I_{DS} constant inspite of an increase in V_{DS} and occurs once V_{DS} exceeds the value of pinch-off voltage V_P. Under this condition, the device will act like a closed switch through which a saturated value of I_{DS} flows. As a result, this operating region is chosen whenever MOSFETs are required to perform switching operations.

Figure 34a shows the transfer characteristics (drain-to-source current I_{DS} versus gate-to-source voltage V_{GS}) of n-channel Enhancement-type MOSFETs. From this, it is evident that the current through the device will be zero until the V_{GS} exceeds the value of threshold voltage V_T. This is because under this state, the device will be void of channel which will be connecting the drain and the source terminals. Under this condition, even an increase in V_{DS} will result in no current flow as indicated by the corresponding output characteristics (I_{DS} versus V_{DS}) shown by Figure 34b. As a result, this state represents nothing but the cut-off region of MOSFET's operation.

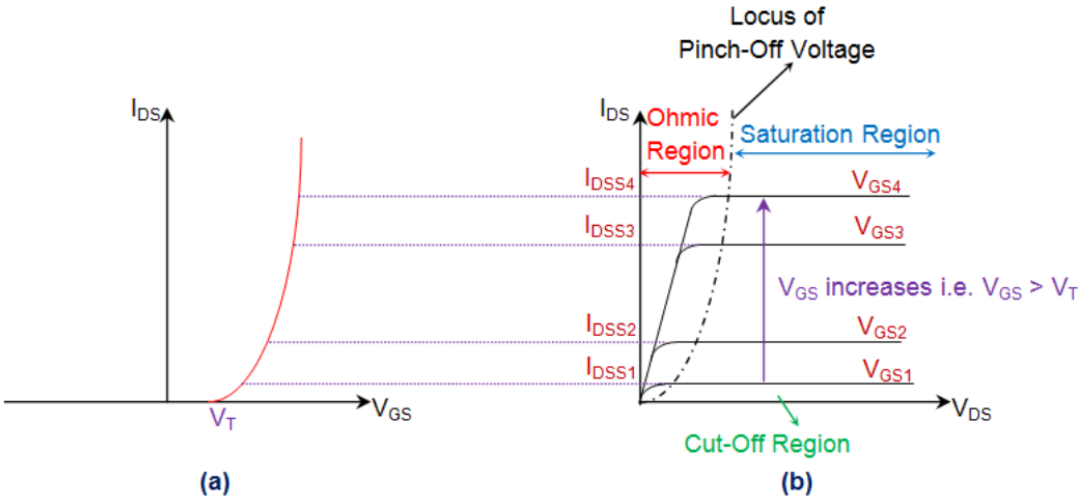


Figure 34: n-channel enhancement type MOSFET (a) transfer characteristics (b) output characteristics

Next, once V_{GS} crosses V_T, the current through the device increases with an increase in IDS initially (Ohmic region) and then saturates to a value as determined by the V_{GS} (saturation region of operation) i.e. as V_{GS} increases, even the saturation current flowing through the device also increases. This is evident by Figure 34b where I_{DSS2} is greater than I_{DSS1} as $V_{GS2} > V_{GS1}$, I_{DSS3} is greater than I_{DSS2} as $V_{GS3} > V_{GS2}$, so on and so forth. Further, Figure 34b also shows the locus of pinch-off voltage (black discontinuous curve), from which V_P is seen to increase with an increase in V_{GS} [33].

In this essay, we measured the I-V characteristics of 2N7000-021, which is a n-channel enhancement mode power MOSFET. Its Gate Threshold Voltage is from 0.8 V to 3 V when V_{DS}=V_{GS}, ID=1 mA and its forward transconductance is 100 mS when V_{DS}=10 V, I_D=200 mA [34]. We measured the transfer characteristics of 2N7000-021 by our analyzer and existing analyzer respectively, which can be seen in Figure 35. Hollow dots indicate the current measured by existing analyzer; the solid line refers to curves measured by our analyzer, we set V_D as 0.05V and 1V respectively, we can see that the curves measured by two analyzers are basically coincident. In order to analyze the similarity of the curves, we plotted the relationship between the current measured by two analyzers at the same input voltage, which can be seen in Figure

36. The black solid points plot the relationship between two measured curves when V_D=0.05 V; the blue solid points plot the relationship between two measured curves when V_D=1 V; the red line represents the function of y=x, which can be used to compare with the linear fit line of the measurement results. We can see the intercept of linear fit lines is very close to 0 and the slope of the linear fit lines is almost 1. Besides, the R-square index of the curve are 0.99997 and 0.99996, which are very close to 1, this indicates that curves measured by two analyzers are strong correlated.

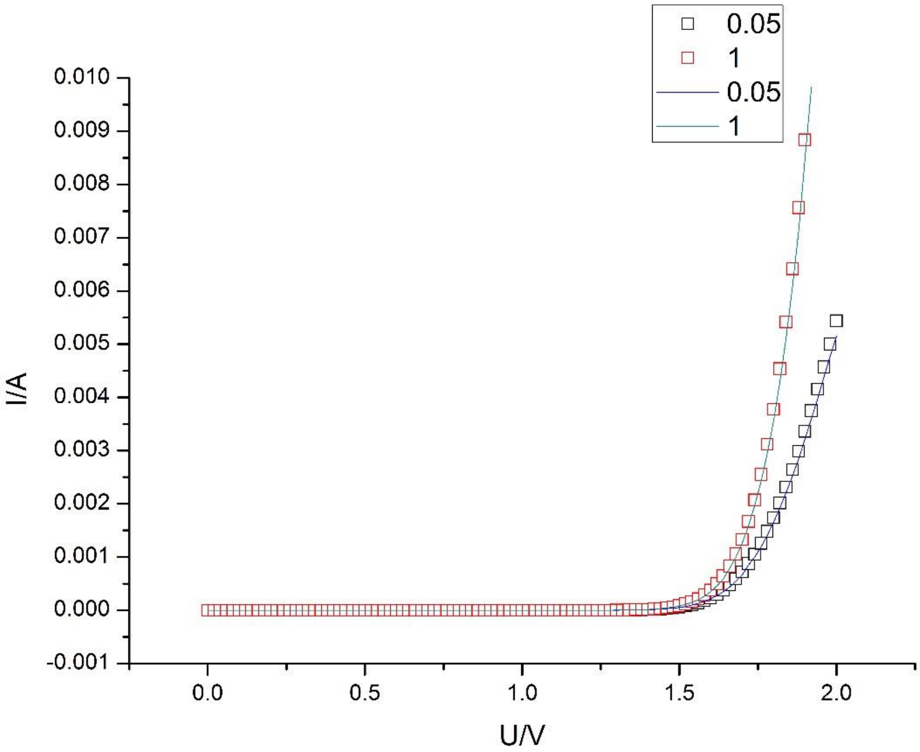
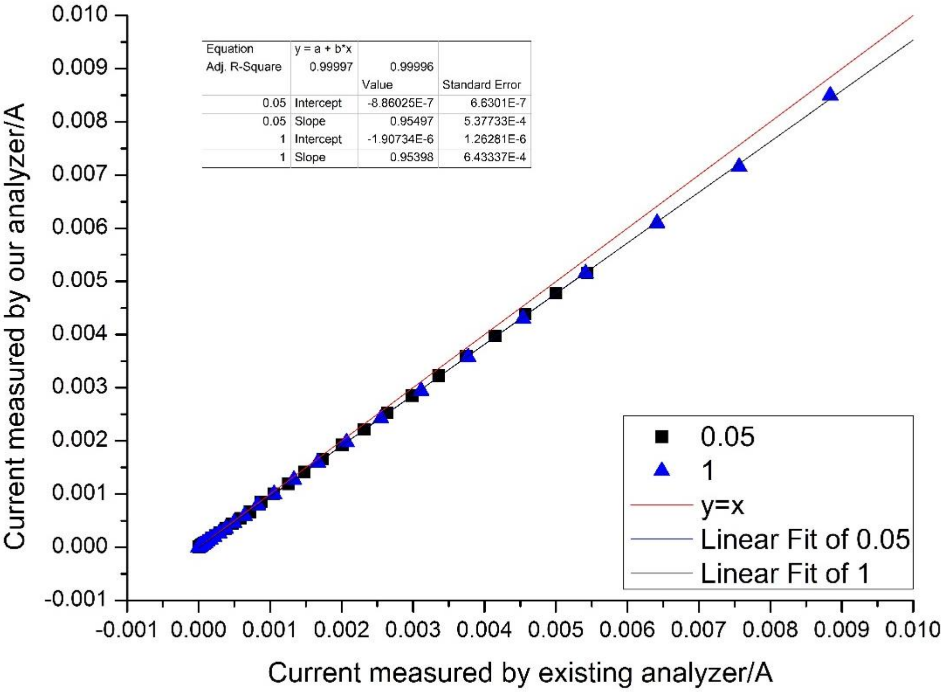


Figure 35: transfer characteristics of 2N7000-021 measured by two analyzers



Equation	y = a + b*x		
Adj. R-Square	0.99997	0.99996	
		Value	Standard Error
0.05	Intercept	-8.86025E-7	6.6301E-7
0.05	Slope	0.95497	5.37733E-4
1	Intercept	-1.90734E-6	1.26281E-6
1	Slope	0.95398	6.43337E-4

Figure 36: Relationship between measured curves (2N7000-021-transfer)

We also analyzed the relationship between error rate and measured current, which can be seen from Figure 37. The black dash line refers to error rate when V_D=0.05 V; the red dash line refers to error rate when V_D=1 V. We can see that the error rate is always at a low level, when the measured current is larger than 10^{-10}A, the error rate is basically zero. Therefore, our analyzer has similar performance to the existing analyzer.

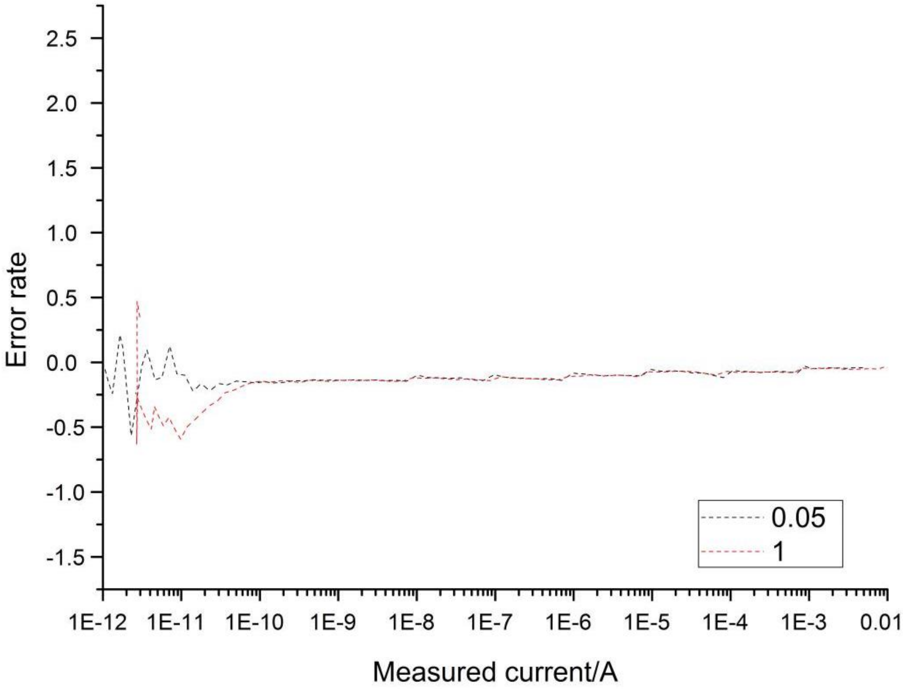


Figure 37: Relationship between error rate and measured current (2N7000-021-transfer)

Then we measured the output characteristics of 2N7000-021, which can be seen in Figure 38. The solid line indicates the curve and measured by our analyzer; the hollow points indicate the curves measured by existing analyzer. The V_{GS} we set is 1.7 V, 1.75 V and 1.8 V, as V_{GS} increases, the saturation current flowing through the device also increases. Besides, we can see that the curve of the linear region is smooth. In order to analyze the similarity of the curves, we plotted the relationship between the current measured by two analyzers at the same input voltage, which can be seen in Figure 39. The green solid points plot the relationship between two measured curves when V_G=1.8 V; the red solid points plot the relationship between two measured curves when V_G=1.75 V; the black solid points plot the relationship between two measured curves when V_G=1.7 V; the blue line represents the function of y=x, which can be used to compare with the linear fit line of the measurement results. We can see the intercept of linear fit lines is very close to 0 and the slope of the linear fit lines is almost 1. Besides, the R-square index of the curves are 0.99927, 0.99951 and 0.99955 respectively, which are very close to 1, this indicates that curves measured by two analyzers are strong correlated. We also analyzed the relationship between error rate and measured current, which can be seen from black dash line, red dash line and blue dash line. We can see that the error rate is always at a low level, not exceeding 0.1. Therefore, our analyzer has similar performance to the existing analyzer.

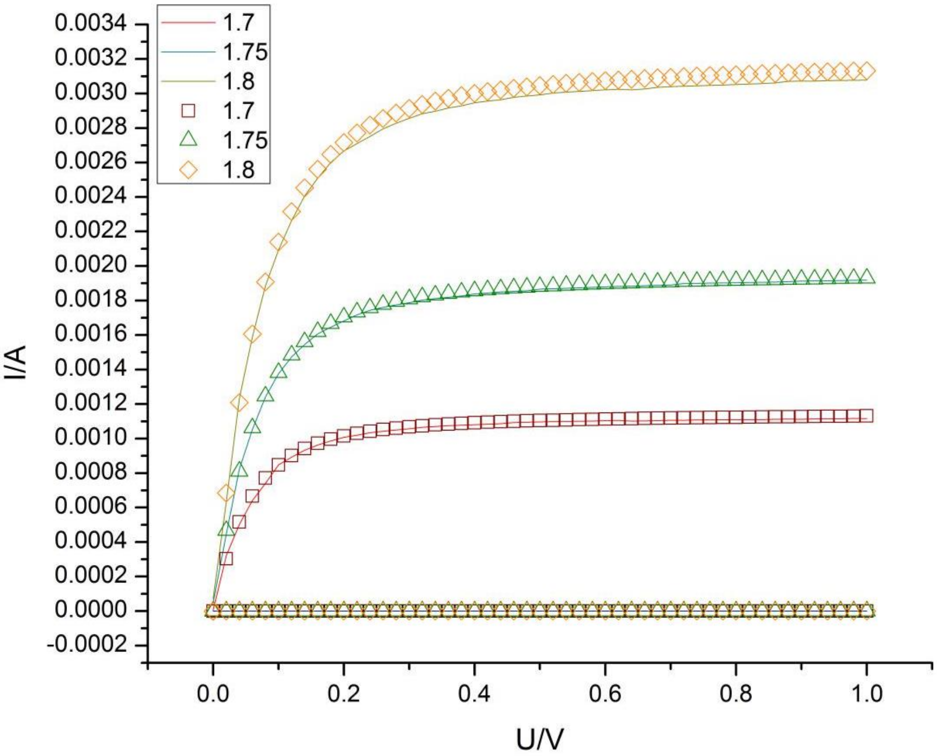
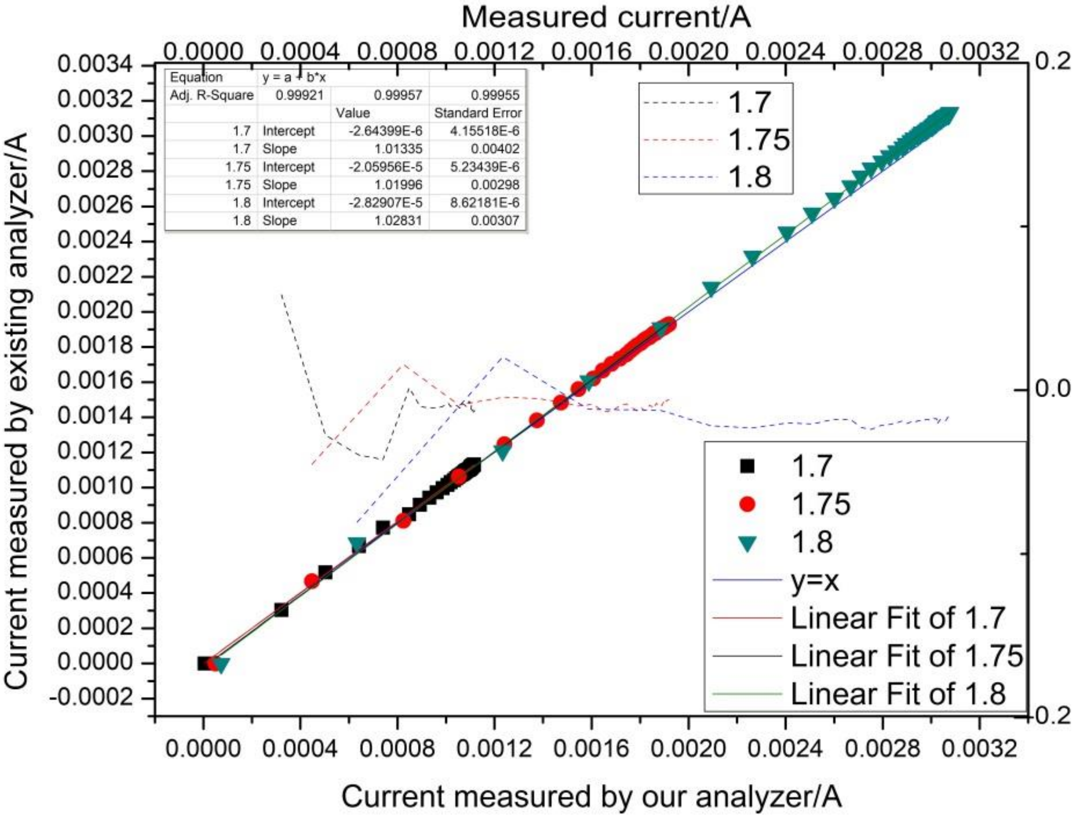


Figure 38: output characteristics of 2N7000-021 measured by our analyzer and existing analyzer



Equation	y = a + b*x		
Adj. R-Square	0.99921	0.99957	0.99955
		Value	Standard Error
1.7	Intercept	-2.64399E-6	4.15518E-6
1.7	Slope	1.01335	0.00402
1.75	Intercept	-2.05956E-5	5.23439E-6
1.75	Slope	1.01996	0.00298
1.8	Intercept	-2.82907E-5	8.62181E-6
1.8	Slope	1.02831	0.00307

Figure 39: Relationship between measured curves (2N7000-021-output)

5 FUTURE WORK

In this Chapter some proposals for future work will be presented and discussed.

Further improve measuring method

From measurement of different standard resistance, we noticed that the ratio of resistance difference to the measured resistance value is a bit large when the measured resistance is 100 Ω. For general purpose resistance measurements and I-V curve generation, 2-point electrical measurements are normally used. However, when the resistance being measured is relatively low, or the resistance of the probes or the contacts is relatively high, a 4-point probe will yield more accurate results [35]. We can predict that through this method, the measurement error can be further reduced.

Further realize the AC pulse measurement function of the amplifier

In the thesis, we designed and verified the transistor DC measurement function of the amplifier. In earlier amplifier performance testing, we also test the AC pulse measurement function of the amplifier, the R_G we use is 500 Ω, the corresponding gain of the operational amplifier is 100, so R_L is 100 times of R_S. The R_S we use is from 10 Ω to 10 MΩ, increasing in number by 10 times, so the corresponding R_L is from 1 kΩ to 1 GΩ, increasing in number by 10 times. The input pulse voltage waveform is a sine wave with an amplitude of 10V and a frequency from 1 Hz to 100 kHz, increasing in number by 10 times. Theoretically, the input pulse waveform should be identical to the output pulse waveform. But in fact, the output waveform will deform more or less and different R_S will deform differently at different frequencies. When R_S is 1 MΩ, which means the measured current is about 1 nA, the output pulse waveform is basically the same as the input pulse waveform at the frequency of 1 Hz to 100 Hz, but the amplitude is severely distorted after exceeding 100 Hz, this may be due to parasitic capacitance between the measurement loop and control loop of relay, when the measured current frequency increases, the impedance of the parasitic capacitance between the measuring circuit and the control circuit is smaller, and the leakage current applied between the control circuit and the measuring circuit is significantly increased, resulting in a large error when the measuring current is small.

We also analyzed the relationship between initial phase with frequency under each R_S. When the measured current is less than 1 μA, the output pulse waveform is basically the same as the input pulse waveform at the frequency of 1 Hz to 1 kHz, but the initial phase is severely drifted after exceeding 1 kHz. Compared with current analyzer, the AC pulse measurement function of the amplifier still need to be improved. In addition, due to the limitation of the power supply voltage, the V_{pp} of the pulse waveform can only reach 30V at most. Therefore, whether it is in the measured frequency and voltage range, or current resolution, our current amplifier has a big gap with the current parametric analyzer.

Improve manufacturing process of the amplifier

Since the current amplifier built in this paper is only a test prototype, except for the PCB board and the operational amplifier, which are provided by the supplier, the soldering of the components is done manually on the welding station, it will inevitably pollute the PCB board during the soldering process. Although we have cleaned the PCB board with board washing water, we cannot completely avoid contamination. As previously analyzed, these contaminants will cause sharp increase in leakage current when the ambient humidity is high. Therefore, we plan to manufacture the whole current amplifier by machining in the future. This requires us to redesign the PCB diagram of the amplifier, including replacing the in-line resistor interface with a SMD resistor interface, taking into account the wiring rules of the previous design, and a fan can be installed on the shield box to facilitate the drying and cooling of the amplifier. It can be predicted that the improvement of these manufacturing processes will surely help to stabilize and improve the performance of the current amplifier.

6 SUMMARY

This paper focused on designing and building the high precision small current amplifier with automatic gain control in integrated semiconductor parameter analyzer. Aim was to make the parameter analyzer we developed comparable to existing analyzers, simple in stricture, easy to carry and low in cost.

The hardware goal, designing and building the circuit of the current amplifier and corresponding PCF module. We designed the circuit called high-side current amplifier which can detect much smaller current like switching current of triode. Besides, the amplifier has adjustable gain to meet measurement needs of large range. Circuit of corresponding PCF module was also designed to provide multi-channel measuring function. Software objective, designing the automatic gain control function, PCF control function and voltage tracking function in current measurement to correct the systematic error in measuring nonlinear components such as diodes. Both of these forms the analyzer's transistor DC measuring function. In this paper, the target was reached and the combination of hardware and software target, building low-cost and simple-structure product, which is easy to use and will be evaluated by customer in the future.

Testing the amplifier was done and compared with the measuring result in resistors, diodes and triodes with current parameter analyzer, it can rival the current analyzer in sensitivity. Based on this, we can be sure that analyzer's transistor DC measuring module is able to function, but we didn't explore how high its sensitivity could be, and we still need to develop other functions like logic analyzing and pulse I-V measurement to make the analyzer be a complete system.

7 Bibliography

[1] Keysight Technologies Ltd. The semiconductor parameter analyzer (device analyzer) basics for your device characterization. [Online]. https://www.keysight.com/main/editorial.jspx?ckey=2317167&id=2317167&nid=-33019.0&lc=eng&cc=US/. [Accessed on 11 May 2019]

[2] Source measure unit. [Online]. https://en.wikipedia.org/wiki/Source_measure_unit/. [Accessed on 12 May 2019]

[3] Kun ZHANG, Fengxing ZHOU, Xiaojuan KE, "Design of Semiconductor Material Characteristic Measuring Instrument Based on STC Microcontroller," Science Technology and Engineering, ISBN: 1671-1815(2014)06-0031-05.

[4] Tektronix Ltd. Keithley 4200A-SCS Parameter Analyzer. [Online]. https://www.tek.com/keithley-4200a-scs-parameter-analyzer/. [Accessed on 18 May 2019]

[5] Keysight Technologies Ltd. B1500A Semiconductor Device Parameter Analyzer/Semiconductor Characterization System Mainframe. [Online]. https://www.keysight.com/en/pd-582565-pn-B1500A/semiconductor-device-analyzer?nid=-33019.536905585&cc=US&lc=eng/. [Accessed on 19 May 2019]

[6] Ruigang MA, Baoqun CUI, Yingjun MA, Chong JIANG, Qinghua HUANG, Bing TANG, Lihua CHEN, "Development of pA Scale Low Current Amplifier," The China Institute of Atomic Energy, 2010.

[7] Small current amplifying. [Online]. https://wenku.baidu.com/view/1ef5de80284ac850ad024251.html. [Accessed on 31 May 2019]

[8] Detailed Explanation and Analysis of Operational Amplifier Parameters. [Online]. https://blog.csdn.net/huangmaiqiu2594/article/details/81558839. [Accessed on 17 July 2019]

[9] Weicheng DING, Fang FANG, Jianbin ZHOU, Min WANG, “The Study on Micro-Direct Current Preamplifier,” Nuclear Electronics &Detection Technology, ISSN: 0258-0934(2009)04-0853-04.

[10] Zhangyan ZHAO, Yongtao LI, Yang XIA, Chaobo LI, Lijun LI, Ruilin LI, “Design on Weak Current Measuring Module in Semiconductor Test Equipment,” Transducer and Microsystem Technologies, ISSN: 1000-9787(2011) 10-0115-03.

[11] Texas Instruments Ltd. Product: DAC8534. [Online]. http://www.ti.com/product/DAC8534. [Accessed 6 June 2019]

[12] Analog Devices Ltd. Product: AD7606. [Online]. https://www.analog.com/en/products/ad7606.html. [Accessed 6 June 2019]

[13] Raspberry Pi Foundation. Product: Raspberry Pi 3 Model B+. [Online]. https://www.raspberrypi.org/products/raspberry-pi-3-model-b-plus/. [Accessed 6 June 2019]

[14] Sergio Franco, “Design with Operational Amplifiers and Analog Integrated Circuits,” Xi’an Jiaotong University Press, ISBN: 978-7-56-053039-0.

[15] Liping CUI, “Circuits Design of Instrumental Amplifier,” Modern Electronics Technique, ISSN: 1004-373X(2009)11-087-03.

[16] Xin LI, “Development of Multi-channel Weak Current Measurement System and Application in Beam Diagnosis,” School of Nuclear Science and Technology, Lanzhou University, 2017.

[17] Lifeng LIU, “Application of the Precise Instument Amplifier IC,” Foreign Electronic Measurement Technology, ISSN: 1002-8978.2003.01.009.

[18] Texas Instrument Ltd. Product: INA116. [Online]. http://www.ti.com/lit/ds/symlink/ina116.pdf. [Accessed 9 June 2019]

[19] Texas Instrument Ltd. Product: PCF8575. [Online]. http://www.ti.com/lit/ds/symlink/pcf8575.pdf. [Accessed 16 June 2019]

[20] Yonglin HUANG, Yutang YE, Naosheng QIAO, Dingyuan WANG, “Design of Automatic Gain Regulation for Linear Array CIS Image Acquisition System,” Process Automation Instrumentation, ISSN: 1000-0380.2011.02.023.

[21] Changfu LI, “Detection System of Weak Current Based on ARM Micro-controller,” School of Control Science and Engineering, Shandong University, 2012.

[22] Fudan Nanofabrication Laboratory. Semiconductor parameter Analyzer [Online]. http://www.nanofab.fudan.edu.cn/e5/ec/c7145a58860/page.htm. [Accessed on 17 August 2019]

[23] Crst Relays Ltd. Product: CRSS1A05. [Online]. http://www.crstrelay.com/datasheet/CRSS1a05-Reed%20Relay.pdf. [Accessed 3 July 2019]

[24] Standex Electronics Ltd. Product: MS05-1A87-75DHR. [Online]. https://4a30d8fd18dae1bf393d-df49f4cedb726ad03ad145d2e3d346bd.ssl.cf5.rackcdn.com/datasheets/42/4205187875e.pdf. [Accessed 4 July 2019]

[25] Shengyi Technology Ltd. Product: S1141. [Online]. http://www.syst.com.cn/uploadfiles/2019/03/20190301102803328.pdf. [Accessed 4 July 2019]

[26] Xiaojian LI, Shanlin ZHAO, Xiaojun FENG, Huaibin LONG, “Applications of Protel DXP (2nd Edition),” Posts & Telecom Press, ISBN: 978-7-115-19081-9/TP.

[27] Guihua JIA, Ping ZHANG, Guorong DENG, “Measurement and Error Analysis of Low Current,” Information and Electronic Engineering, ISSN: 1672-2892(2009)06-0609-04.

[28] Henri Sino. (2011) Electromagnetic Interference (EMI) Filtering Reduces Errors in Precision Analog Applications. [Online]. https://www.analog.com/en/analog-dialogue/articles/how-emi-filtering-reduces-errors.html. [Accessed 6 July 2019]

[29] Weixun WANG, "Research on Detection of Weak Direct Current," School of Mechanical and Precision Instrument Engineering, Xi'an University of Technology, 2007.

[30] Hanli LIAN, "Theory analysis on volt - ammetry characteristic curves of diode," Journal of Xi'an University of Post and Telecommunications, ISSN: 1007-3264(2008)05-0150-03.

[31] Guangmeng CHEN, "Fundamentals of Analog Electronics," Fudan University Press, ISBN: 978-7-30-906858-0.

[32] Huaguang KANG, "Fundamentals of Electronic Technology (Analog Section)," Higher Education Press, ISBN: 978-7-04-038480-2.

[33] SeCoS Corporation. Product: 2N7000-021. [Online]. http://www.secosgmbh.com/datasheet/products/MOSFET/TO-92/2N7000.pdf. [Accessed 20 August 2019]

[34] MOSFET Characteristics. [Online]. https://www.electrical4u.com/mosfet-characteristics/. [Accessed 20 August 2019]

[35] Hochberg, J. ; Foster, P.: Four Point Probe I-V Electrical Measurements Using the Zyvex Test System Employing a Keithley 4200. / Zyvex Instruments. 2009. – Forschungsbericht.