模拟电路元件手册
Analog Components Handbook

丁毅

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序言

本书为笔者本科时的“模拟电路元件手册”，对学习过程中接触较多的模拟元件作了简要的介绍和总结，同时也是具体元件的测试记录本。笔者所使用过的大多数元件，都进行了较为详细的实际测试，结果记录在本手册中。本书不仅能帮助读者快速了解各类模拟元件的基本信息，还能为读者的元件选型提供参考数据，进而提高电路的设计效率。

本手册将长期更新，读者可到我的 GitHub 下载手册的最新版本 https://github.com/YiDingg/LatexNotes，也可以在我的个人网站 待更新 上找到相关资料。

事实上，有相当一部分元件（例如 Operational Amplifier ）是基础元件所构成的模块化电路。在本书，我们不会详谈如何搭建出这些模块电路，而是讨论如何对这些模块建立正确的认识，介绍在不同情况下应该选用怎样的模型进行分析，以达到足够高的精度，同时尽可能地降低模型复杂度。实现它们的具体电路，以及 Oscillators, Amplifiers 等模块元件及其应用电路，会放到另一本书《模拟电路手册》中，读者可到网址 GitHub (https://github.com/YiDingg/LatexNotes/tree/main/[Notes] Electornic Circuits Manual) 自行下载和阅读。

为了提高读者的自学效率，笔者在这里推荐几个免费而优秀的电子学习网站：

(1) Electornics Tutorials : 这个网站提供了丰富的电子学习资料，包括 Transistors, Amplifiers, Diodes, Filters 等，还提供了很多实用的电子工程师工具，例如在线电阻电感电容计算器等；

(2) Learn About Electronics : 这个网站提供了电子学习的基础和进阶知识，包括 Semiconductors, Amplifiers, Oscillators, Power Supplies 等，最令人惊喜的是几乎所有资料都提供了 PDF 下载，方便读者下载后自行学习；

(3) Electronics Lab : 这个网站不仅开源了很多电子电路设计实例，包括基础电路、模拟电路、数字电路等，还提供了丰富的学习资源（文章）在 here；

(4) Microchip : 这是 Microchip 官方的开发者帮助网站，提供了大量的电子元件的 Data Sheet, Application Notes, Reference Manuals 等，是学习 Microchip 产品的重要参考网站，当然，在这里也可以找到与模拟电路、数字电路相关的的学习资料；

(5) Analog Devices (https://wiki.analog.com/university/courses/tutorials/index) : 这是 Analog Devices 官方的 Wiki 网站，提供了大量的电子学习资料，包括 Analog Electronics, Mixed Signal Electronics (Systems), Signals and Systems 以及 some e-books in PDF ，是学习模拟电路的优秀网站。

(6)

(7) All About Circuits (https://www.allaboutcircuits.com/technical-articles/) : 这个网站提供了丰富的电子电路和教程，同时收集了大量的模拟电路设计参考。

由于个人学识浅陋，认识有限，文中难免有不妥甚至错误之处，望读者不吝指正，也欢迎内容、排版等方面的建议。读者可以将错误或建议发送到我的邮箱 dingyi233@mails.ucas.ac.cn，也可以到笔者的 GitHub (https://github.com/YiDingg/LatexNotes) 上提 issue ，衷心感谢。

Preface

This is an analog components handbook during my undergraduate studies. It provides a summary of the components that I encountered frequently during my studies, and is also a test record book for specific components. Most of the components I have used have been tested in detail, and the results are recorded in this handbook. This book can not only help readers quickly understand the basic information of various analog components, but also provide reference data for readers' components selection, thereby improving the efficiency of circuit design.

This handbook will be updated for a long time. Readers can download the latest version of the handbook from my GitHub https://github.com/YiDingg/LatexNotes, and can also find related materials on my personal website to be updated.

Additionally, there are a variety number of components (such as Operational Amplifier) that are actually modular circuits comprised of basic components. In this book, we will not delve into how to build these advanced components, but rather discuss how to properly understand these components (modular circuits), and explore the models that should be used for analysis in different situations to achieve sufficient accuracy, while minimizing model complexity. The specific circuits for constructing these components, such as oscillators, amplifiers, etc., will be included in another book *"Analog Circuits Handbook"*, which can also be found on my GitHub > YiDingg > Analog Circuits Handbook.

In order to better enhance the reader's self-study efficiency, I recommend several free and excellent online learning websites here:

(1) Electronics Tutorials (https://www.electronics-tutorials.ws): This website provides a wealth of electronic learning resources, including Transistors, Amplifiers, Diodes, Filters, and many practical tools for electronic engineers, such as an online resistor, inductor, and capacitor calculator.

(2) Learn About Electronics (https://www.learnabout-electronics.org): The website provides basic and advanced knowledge of electronics, including Semiconductors, Amplifiers, Oscillators, Power Supplies, and the best part is that almost all the materials are provided in PDF format for easy download and offline learning.

(3) Electronics Lab (https://www.electronics-lab.com): This website not only open-source many electronic circuit design examples, including basic circuits, analog circuits, and digital circuits, but also provides a wealth of learning resources and articles here (https://www.electronics-lab.com/articles).

(4) Microchip (https://developerhelp.microchip.com): This is Microchip's official developer help website which provides a wealth of data sheets, application notes, and reference manuals for electronic components. It is an important reference website for learning about Microchip products, and of course, you can also find learning materials related to analog circuits and digital circuits here.

(5) Analog Devices (https://wiki.analog.com/university/courses/tutorials/index) : This is Analog Devices' official Wiki website, which provides a wealth of electronic learning materials, including Analog Electronics, Mixed Signal Electronics (Systems), Signals and Systems, and some eBooks in PDF, which is an excellent website for learning analog circuits.

(6) All About Circuits (https://www.allaboutcircuits.com/technical-articles/): This website provides a wealth of electronic circuits and tutorials, and collects numerous analog circuits.

Due to my own limited knowledge and understanding, there may be inappropriate or even incorrect parts in this article. I sincerely hope readers will point out any errors or inaccuracies. Readers can send errors to my email address dingyi233@mails.ucas.ac.cn, or report issues on my GitHub (https://github.com/YiDingg/LatexNotes) with my utmost gratitude.

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Chapter 1 Diodes

1.1 Introduction

Diodes are the most famous semiconductor devices, widely used in various circuits. They are made of semiconductor materials, mainly silicon (used to be selenium and germanium), and various compounds and metals are added according to the required functions.

Briefly speaking, diodes have unidirectional conductivity, allowing current to flow in only one direction. Fig.1.1 are the IEEE standard circuit symbols of diodes, and you can refer to reference [1] and [2] for more details. Classified by different principles, diodes can be divided into the following types:

(1) PN junction diode (general diode, PN 结二极管, 通用二极管)
(2) Schottky diode (肖特基二极管)
(3) Zener diode (齐纳二极管)
(4) tunnel diode (隧道二极管)
(5) LED (light-emitting diode, 发光二极管)
(6) photo diode (光电二极管)

According to different application scenarios (circuits), they can be roughly divided into several types:

(1) rectifier diode (整流二极管)
(2) switching diode (开关二极管)
(3) regulator diode (稳压二极管)
(4) limiter diode (限幅二极管)
(5) freewheel diode (续流二极管)
(6) point contact diode (点接触二极管)
(7) LED (light-emitting diode, 发光二极管)
(8) varible capacity diode (varicap diode, 变容二极管)
(9) TVS (Transient Voltage Suppressor, 瞬态抑制二极管)

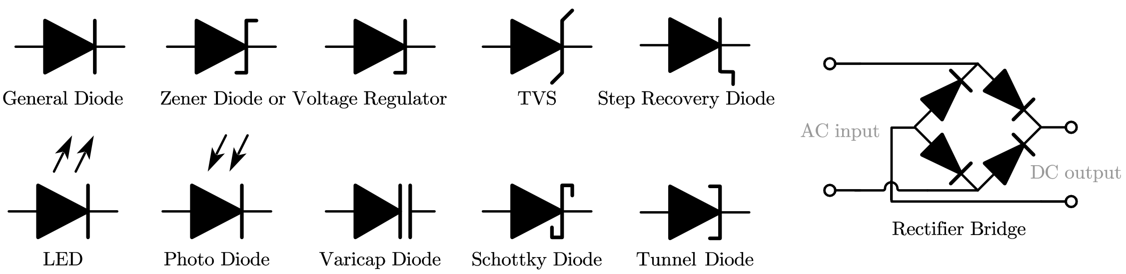


Figure 1.1: Diodes Circuit Symbols (IEEE Standard)

Fig.1.2 shows several common diodes, and they are respectively:

(1) Three kinds of power rectifiers.
(2) A point contact diode (glass encapsulation) and a Schottky diode.
(3) A small signal silicon diode.
(4) Zener Diodes with glass or black resin encapsulation (树脂封装).
(5) A selection of light emitting diodes.

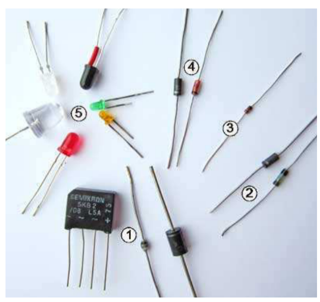


Figure 1.2: Some Common Diodes

1.2 General Diode (通用二极管)

1.2.1 Concepts and Models

Depited in Figure 1.3, The current flowing through a general diode (PN junction diode) satisfis:

$$I_\mathrm{D} = I_\mathrm{S}\left(\exp\frac{V_\mathrm{D}}{V_\mathrm{T}} - 1\right) \tag{1.1}$$

Where $V_\mathrm{T} = \frac{k_B T}{q_e} \approx 26$ mV at 300 K, V_D is the diode forward voltage, and I_S is the saturation current (bewteen 1 nA and 100 nA, typically 7 nA) given by:

$$I_\mathrm{S} = Aq_e n_i^2\left(\frac{D_n}{N_A L_n} + \frac{D_p}{N_D L_p}\right) \tag{1.2}$$

Where A is the junction area, q_e is the electron charge, n_i is the intrinsic carrier concentration, D_n and D_p are the diffusion coefficients of electrons and holes, N_A and N_D are the doping concentrations of the P and N regions, and L_n and L_p are the diffusion lengths of electrons and holes. n_i is a function of temperature, and can be calculated by:

$$n_i = 5.2\, T^{\frac{3}{2}} \exp\left(-\frac{E_g}{2k_B T}\right) \times 10^{15} \tag{1.3}$$

For intrinsic silicon, $E_g = 1.12\ \mathrm{eV} = 1.792 \times 10^{-19}$.

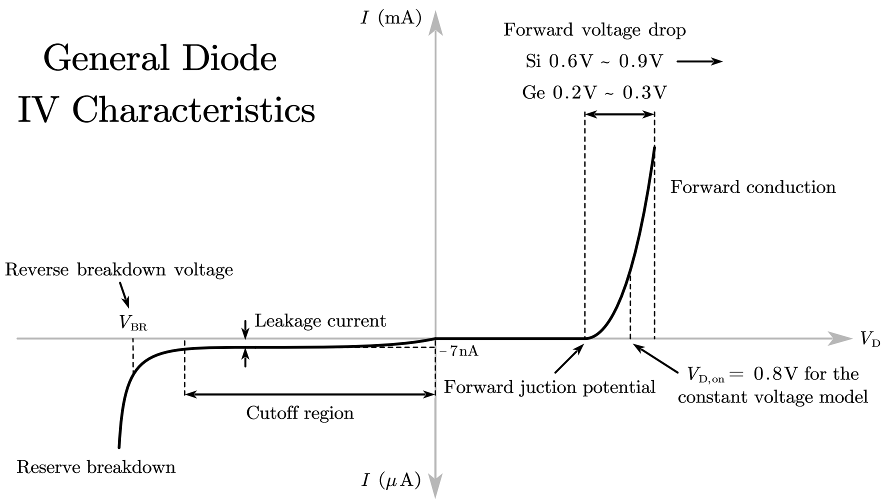
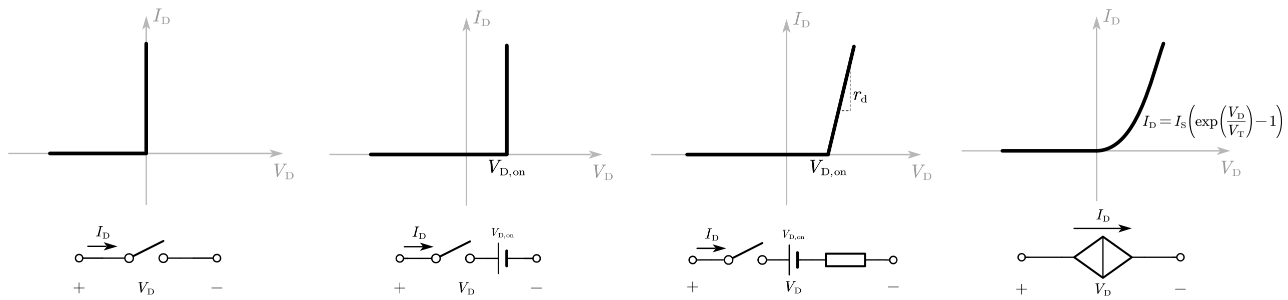


Figure 1.3: IV Characteristics of a General (Junction) Diode

Equation (1.1) is called the expotential model of diode, which is a good approximation for most situations, but too complicated for circuit analysis (especially if there are a lot of components). Therefore, we prefer to use some more simple models.



(a) Ideal Diode Model **(b) Constant-Voltage Model** **(c) Piecewise Linear Model** **(d) Expotential Model**

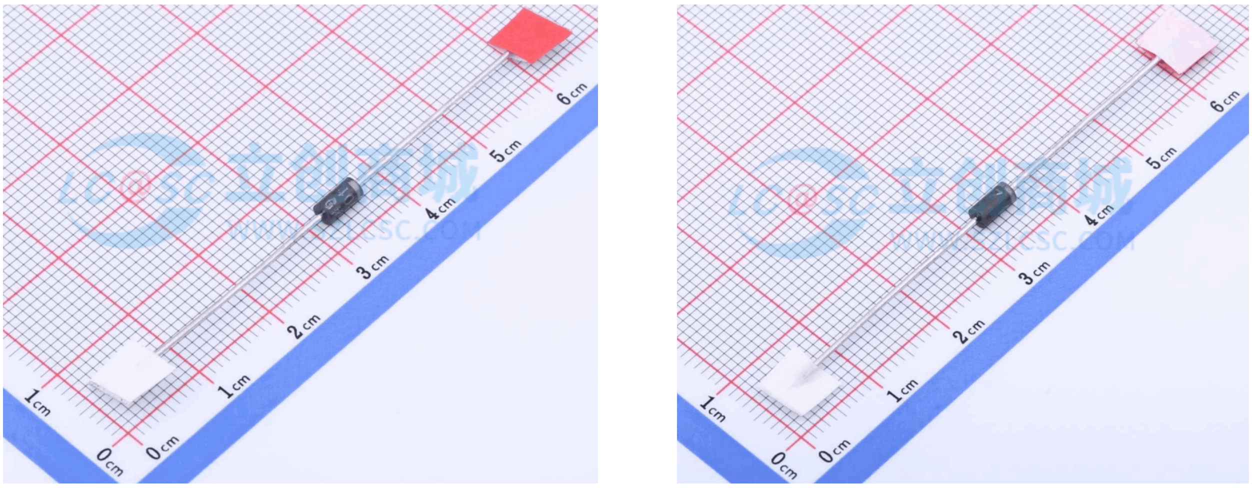
Figure 1.4: Common Models of General Diodes

Fig.1.4 shows several common models of diodes, including ideal diode model, constant voltage drop model, and piecewise linear model. Here are some tips for choosing the right model:

(a) Switch model: to gain an intuition into the circuit, ideal mode could be a great choice.
(b) **Switch-Source model**: a better choice to analysis the exact circuit behavior, also **the most commonly used**.
(c) Switch-Source-Resistor model: an alternative to replace the expotential diode.
(d) Expotential model: the most accurate model, but too complicated for common circuit analysis, usually used in the small-signal analysis.

1.2.2 1N4007 [GOODWORK, 固得沃克]

Manufactured by GOODWORK (固得沃克, Jiangsu, China), 1N4007 (and 1N4001, ..., 1N4006) is a general/rectifier/power diode, commonly used in rectifier circuits, etc. You can find it on GOODWORK Official Website or LCSC (立创商城).

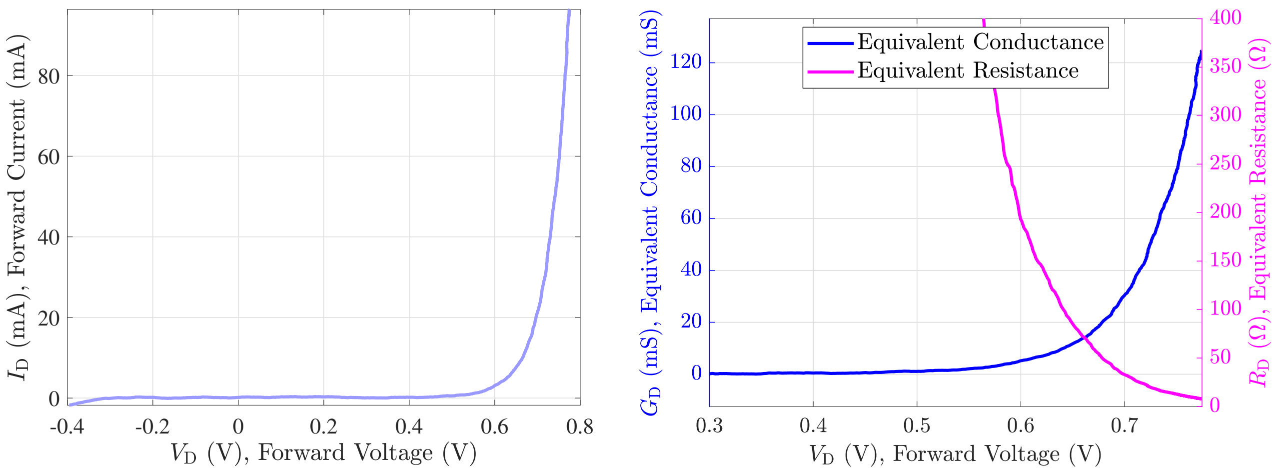


(a) The front side

(b) The back side

Figure 1.5: 1N4007 [GOODWORK (固得沃克)]

We won't repeat the specific parameters in the Data Sheet. To get the actual I-V characteristics of Diodes 1N4007, the test circuit is shown in Fig.1.7, and the results are shown in Fig.1.6.



(a) Voltage-Current Characteristics

(b) Resistance Characteristics

Figure 1.6: Static Operation Characteristics of 1N4007

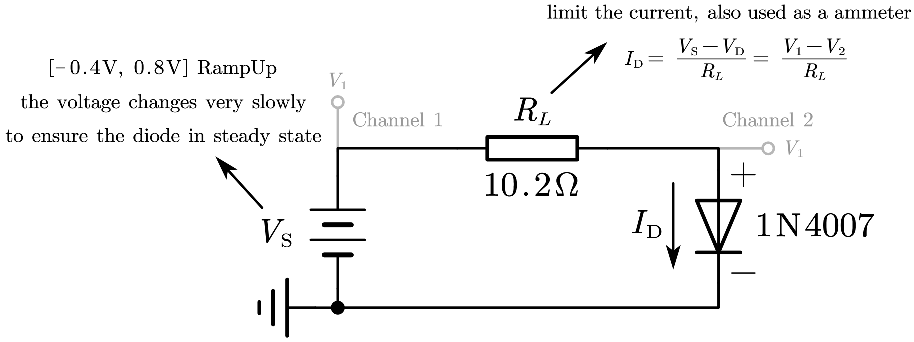


Figure 1.7: Test Circuit for the Static Operation Characteristics of 1N4007

1.3 Zener Diode (齐纳二极管)

1.4 LED (Light Emitting Diode, 发光二极管)

1.4.1 XL-302 [XINGLIGHT, 成兴光]

XL-302SURD (red)、XL-302SURC (white)、XL-302UYD (yellow)、XL-302UYC (green)、是由 XINGLIGHT (成兴光, 中国广东) 生产的 LED，可以在 立创商城 或 XINGLIGHT 官网 上找到它们。其实物图如下：

1.4.2 LED [Txxbao, 某宝]

在某宝中购买大小和外观与 XL-302 相同的 LED ，其电气特性如下：

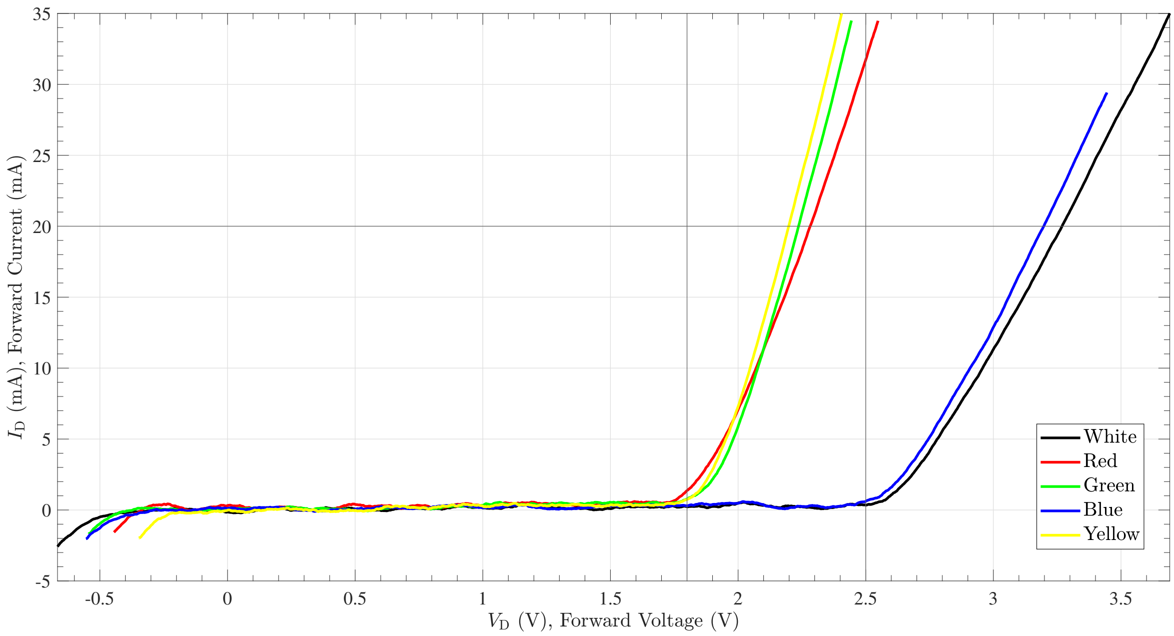


Figure 1.8: Voltage-Current Characteristics

由图可以看到，黄绿红三色导通电压 V_{th} 和 20 mA 工作压降 V_D 分别为：

$$\text{yellow, green, red:}\ \ \boldsymbol{V_{th} = 1.8\ V}, \quad \boldsymbol{V_D = 2.3\ V} \tag{1.4}$$

而蓝色和白色 LED 的导通电压 V_{th} 和 20 mA 工作压降 V_D 分别为：

$$\text{blue, white:}\ \boldsymbol{V_{th} = 2.6\ V}, \quad \boldsymbol{V_D = 3.3\ V} \tag{1.5}$$

1.5 Schottky Diode (肖特基二极管)

Chapter 2 Transistors

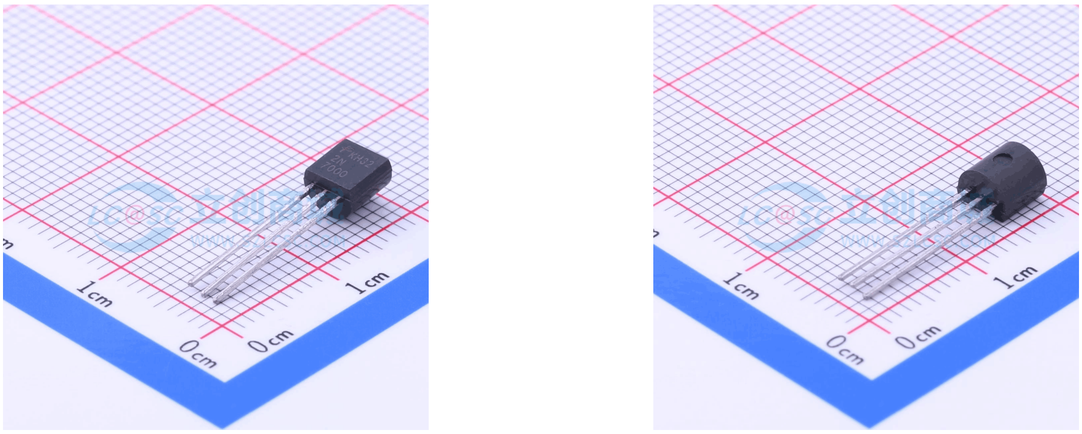
2.1 BTJ (Bipolar Transistor Junction, 双极型晶体管, 三极管)

2.2 JFET (Junction Field Effect Transistor, 结型场效应晶体管)

2.3 MOSFET (Metal-Oxide -Semiconductor Field Effect Transistor, 金属氧化物半导体场效应晶体管)

2.3.1 2N7000 [onsemi (安森美)]

2N7000 [onsemi (安森美)] 是由 onsemi 公司生产的 N-Channel Enhancement Mode Field Effect Transistor (N-Channel Enhancement MOSFET)，可以在 立创商城 或 GOODWORK 官网 上找到它。其实物图如下：



(a) The front side (b) The back side

Figure 2.1: 2N7000 [onsemi (安森美)]

用经典反相器结构，取合适的电阻 R_L 用作电流表（我们这里取 $R_L = 5.2\Omega$），固定 V_{GS}，同时改变 V_{DS}，可以得到 MOS 的工作特性 (Operation Characteristics) $I_{\mathrm{DS}} = I_{\mathrm{DS}}(V_{\mathrm{DS}})$，这包括了导通特性 (On-Region Characteristics) 和体二极管特性 (Body Diode Characteristics)。

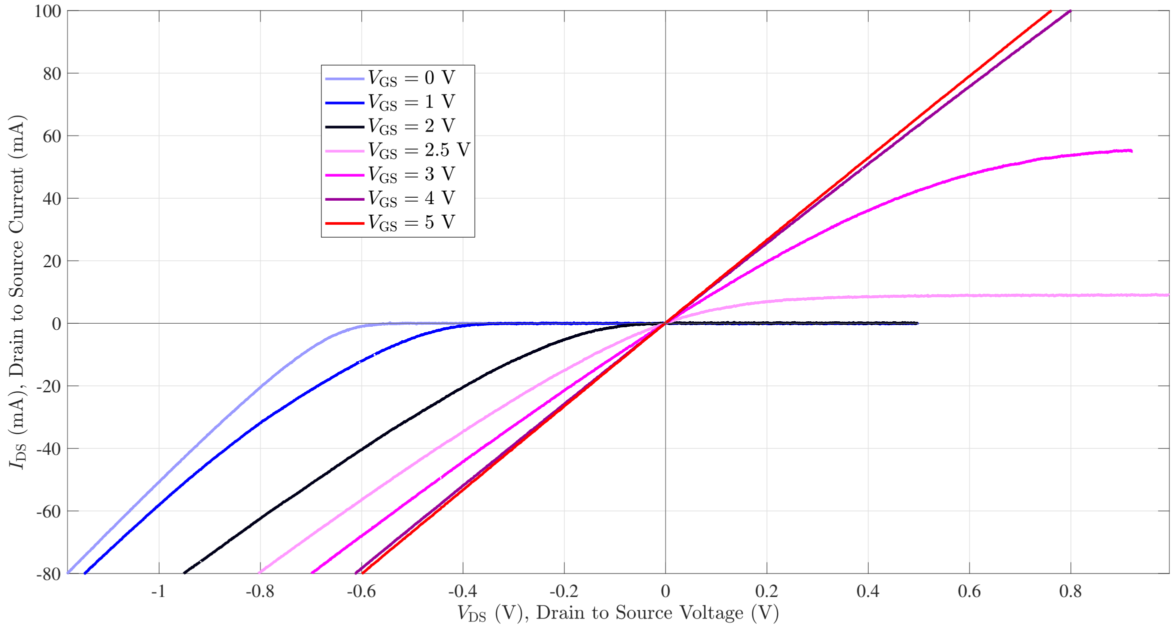


Figure 2.2: Operation Characteristics of 2N7000

依据实际测得的数据，可以计算出 MOS 的等效电导特性 (Equivalent Conductance Characteristics)，如下图所示：

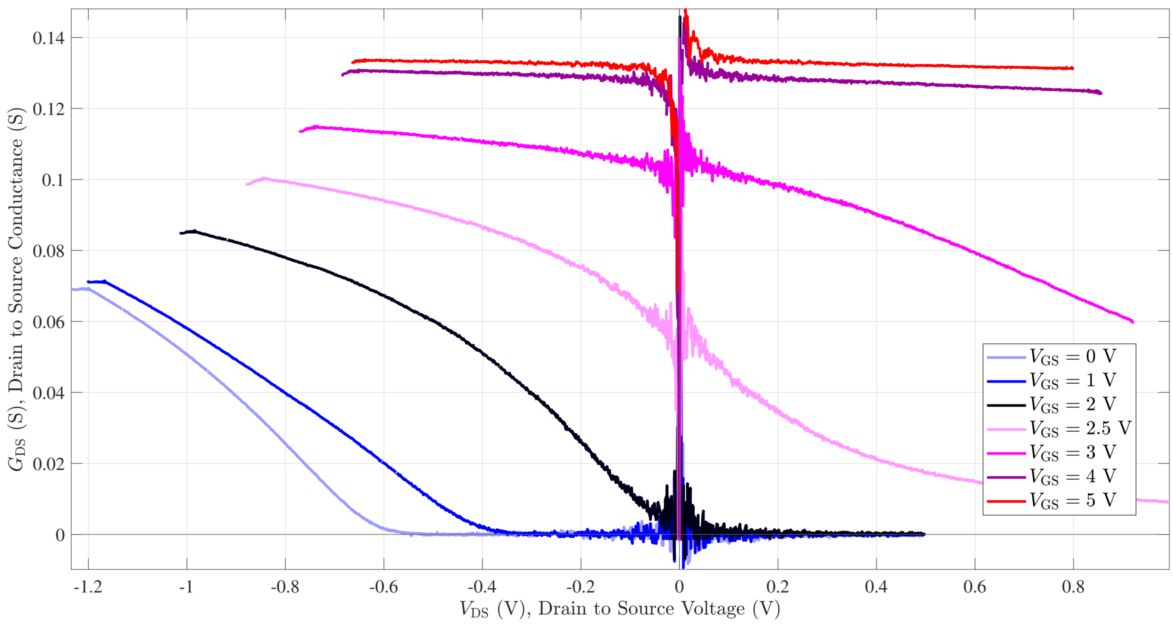


Figure 2.3: Equivalent Conductance Characteristics of 2N7000

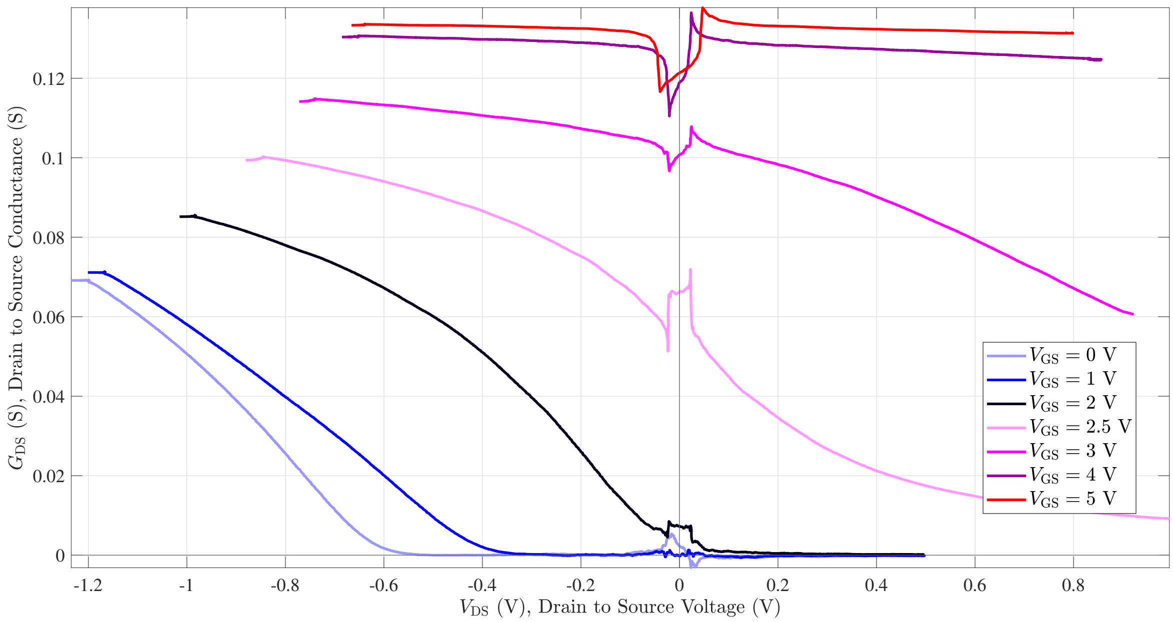


Figure 2.4: Filtered Equivalent Conductance Characteristics of 2N7000

固定 V_{DS}，改变 V_{GS}，串联万用表以测量 I_{DS}，得到 2N7000 的转移特性曲线 $I_{DS} = I_{DS}(V_{GS})$ 如下：

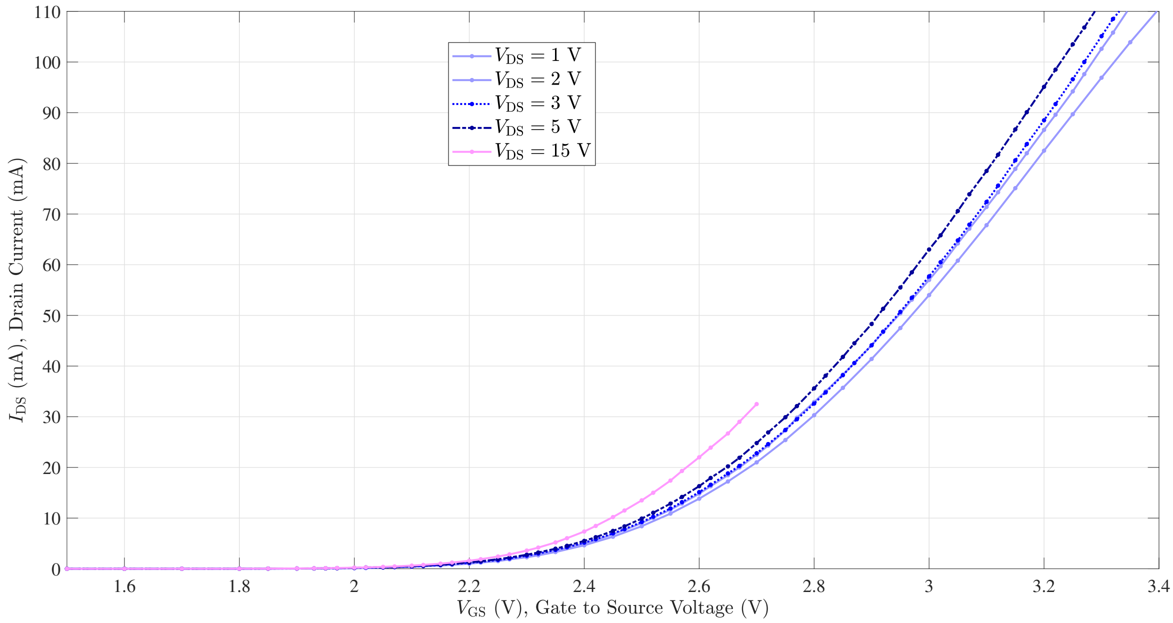


Figure 2.5: Transfer Characteristics of 2N7000

上图中 $V_{DS} = 15$ V 时仅测到 $V_{GS} = 2.7$ V，这是因为往后 MOS 管发热严重，温度不断上升，无法得到稳定示数。用 $V_{DS} = 15$ V 时测得的数据拟合饱和电流公式 $I_{DS} = \frac{K}{2}(V_{GS} - V_T)^2$，其中 K 和 V_T 是待定参量，得到：

$$\boldsymbol{V_T = 2.109\ \mathrm{V}, \quad K = 0.182\ \mathrm{A \cdot V^{-2}} = 182\ \mathrm{mA \cdot V^{-2}}} \tag{2.1}$$

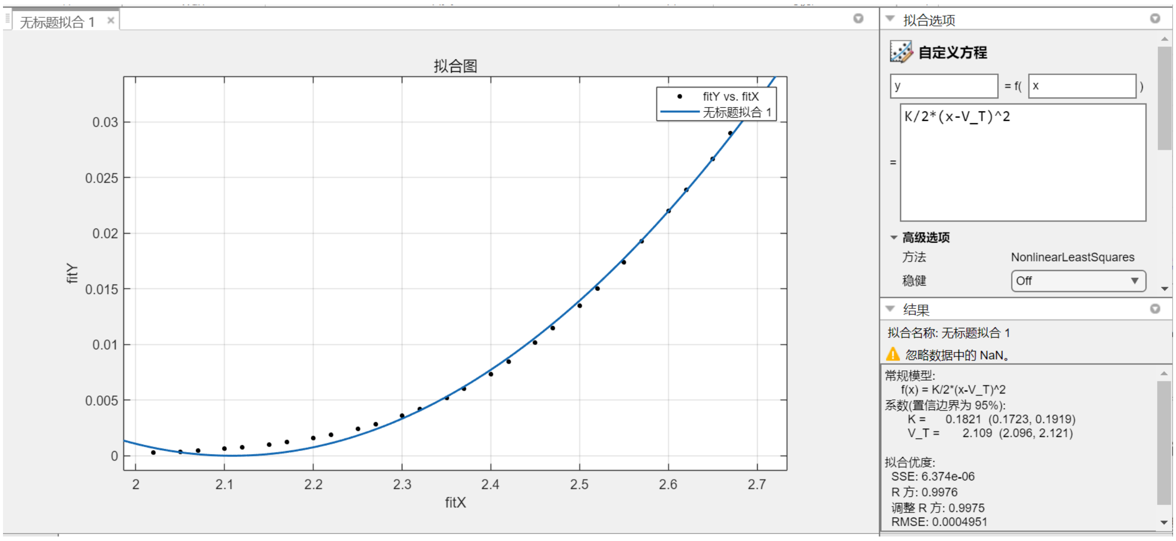


Figure 2.6: Threshold Voltage of 2N7000

用 $V_{\text{DS}} = 5\ \text{V}$ 时的数据，拟合得到

$$\boldsymbol{V_{\text{T}} = 2.156\ \text{V}, \quad K = 0.1742\ \text{A} \cdot \text{V}^{-2} = 174.2\ \text{mA} \cdot \text{V}^{-2}} \tag{2.2}$$

2.3.2 FinFET (Fin Field-Effect Transistor, 鳍式场效应晶体管)

2.4 MODFET (Modulationdoped Field-Effect Transistor, 调制掺杂场效应晶体管)

2.5 Darlington Transistors (达林顿晶体管)

Chapter 3 Inductors

3.1 Inductors and Its Unideal Model

3.1.1 Automatic Impedance Measurement

3.1.2 2 mH DR Magnetic Core [Unknow Brand]

We use AD1 (Analog Discovery 1) to measure the impedance of a 2 mH DR magnetic core inductor of an unkown brand. Below are the product picture and its measurement result.

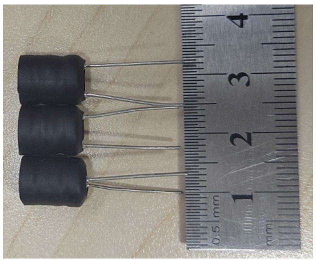


Figure 3.1: 2 mH DR magnetic core

Table 3.1: Parameters of the 2 mH DR magnetic core inductor

L_{eq}	ESR	C_p
1.99 mH @ 1 KHz 1V 1.96 mH @ 10 KHz 1V 1.90 mH @ 100 KHz 1V	3.05 Ω @ DC 1V 3.08 Ω @ 1 KHz 1V 3.18 Ω @ 10 KHz 1V 5.67 Ω @ 100 KHz 1V	113.8 pF using 1.99 mH $f_c = 333887$ Hz

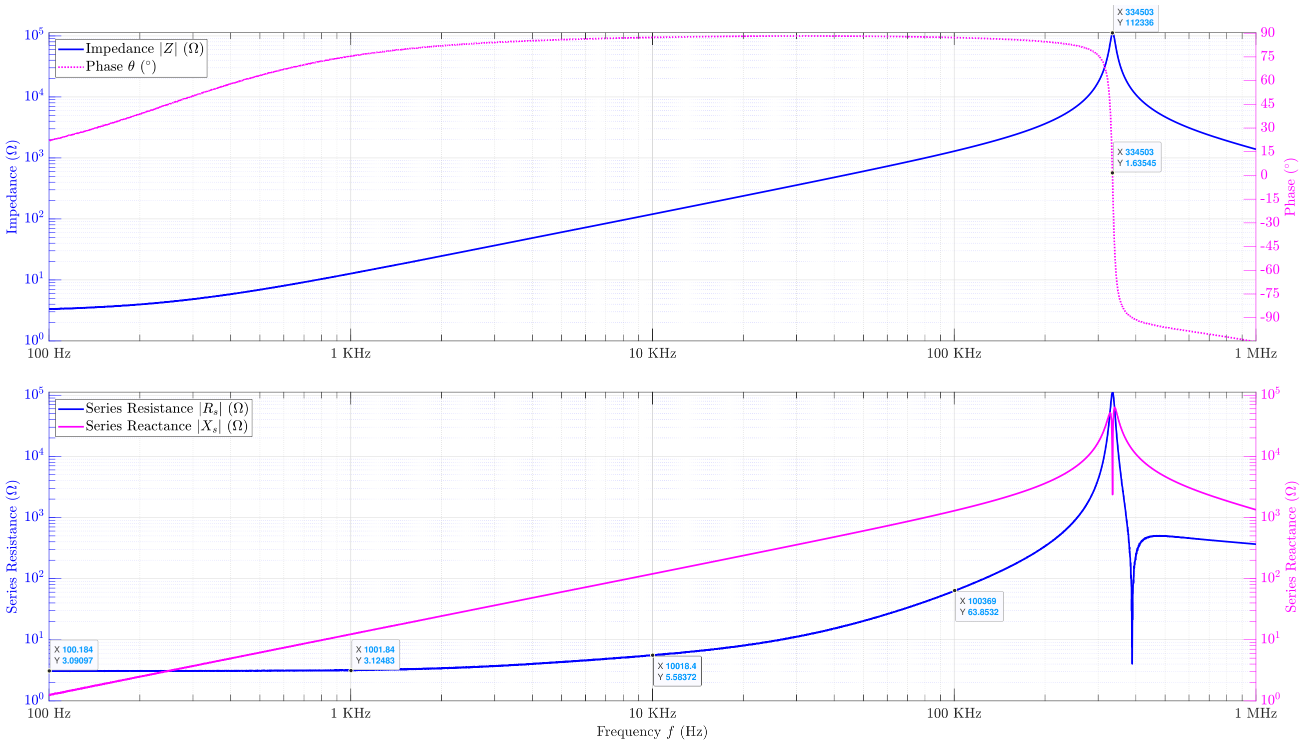


Figure 3.2: Impedance characteristics of the 2 mH DR magnetic core inductor

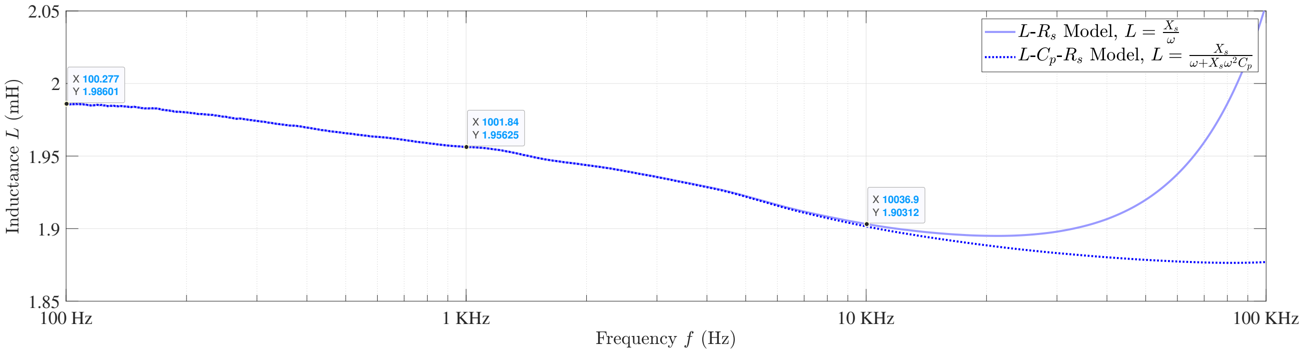


Figure 3.3: Construct the equivalent models of the inductor

3.1.3 100 mH DR Magnetic Core [Unknow Brand]

Use the same method to measure the impedance, and the results are shown below.

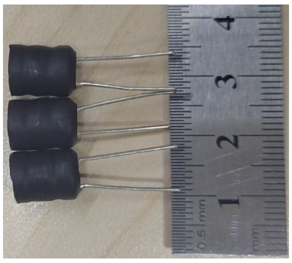


Figure 3.4: 100 mH DR magnetic core

Table 3.2: Parameters of 100 mH DR magnetic core inductor

L_{eq}	ESR	C_p
1.99 mH @ 1 KHz 1V 1.96 mH @ 10 KHz 1V 1.90 mH @ 100 KHz 1V	162.1 Ω @ DC 1V 163.9 Ω @ 1 KHz 1V 174.8 Ω @ 10 KHz 1V 490.3 Ω @ 100 KHz 1V	114.6 pF using 100.7 mH $f_c = 47162.8$ Hz

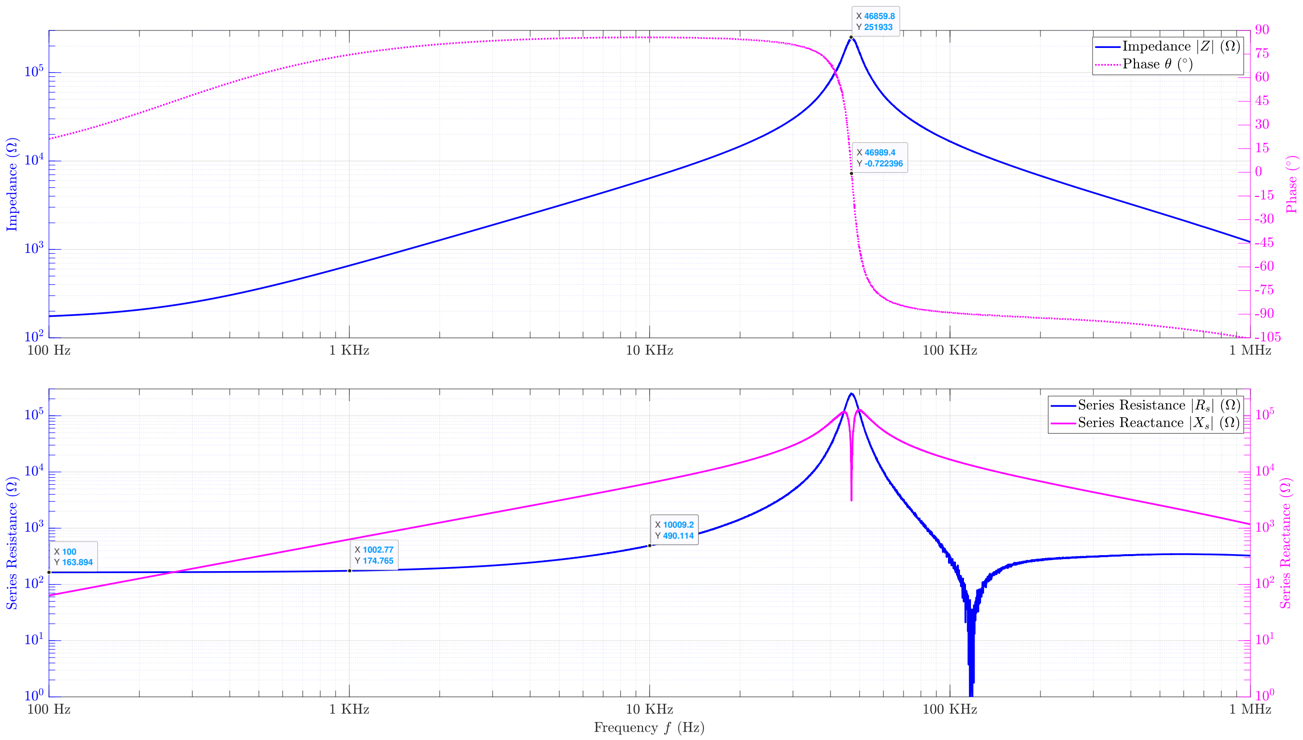


Figure 3.5: Impedance characteristics of the 100 mH DR magnetic core inductor

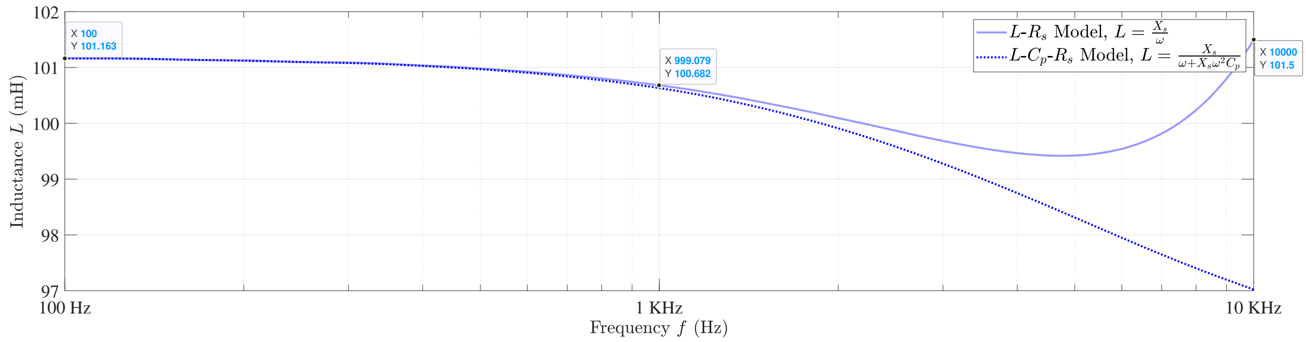


Figure 3.6: Construct the equivalent model of the inductor

Chapter 4 Capacitors

4.1 Capacitors and Its Unideal Model

4.2 Aluminum Electrolytic Capacitor (铝电解电容)

4.2.1 220 uF 16V Aluminum Electrolytic Capacitor

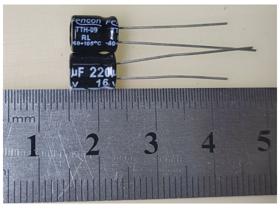


Figure 4.1: 220 uF 16V Aluminum Electrolytic Capacitor

Table 4.1: Parameters of the 220 uF 16V Aluminum Electrolytic Capacitor

C_{eq}	ESR	L_s
186.7 uF @ 100 Hz 0.5V	0.52 Ω @ 1 KHz 0.5V	18.82 nH
178.1 uF @ 1 KHz 0.5V	0.28 Ω @ 10 KHz 0.5V	using 178.1 uF
186.7 uF @ 10 KHz 0.5V	0.26 Ω @ 100 KHz 0.5V	$f_c = 86939.9$ Hz

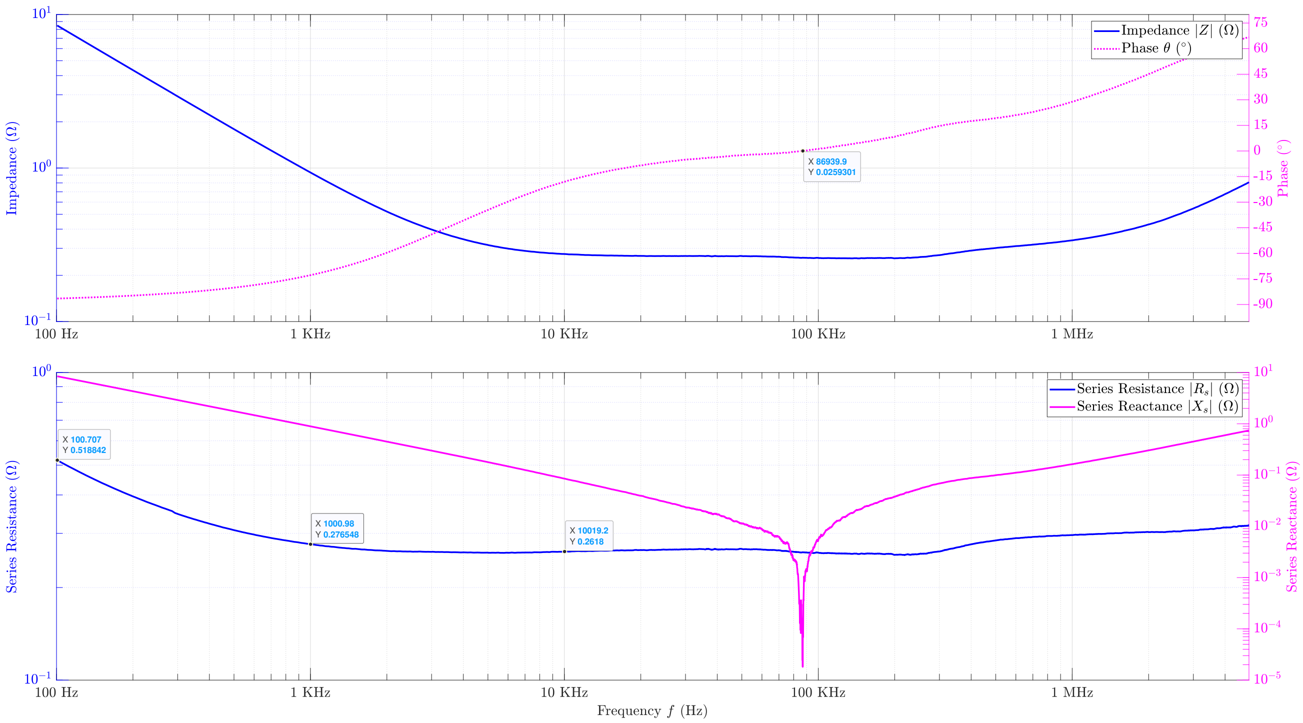


Figure 4.2: Impedance characteristics of the 220 uF 16V Aluminum Electrolytic Capacitor

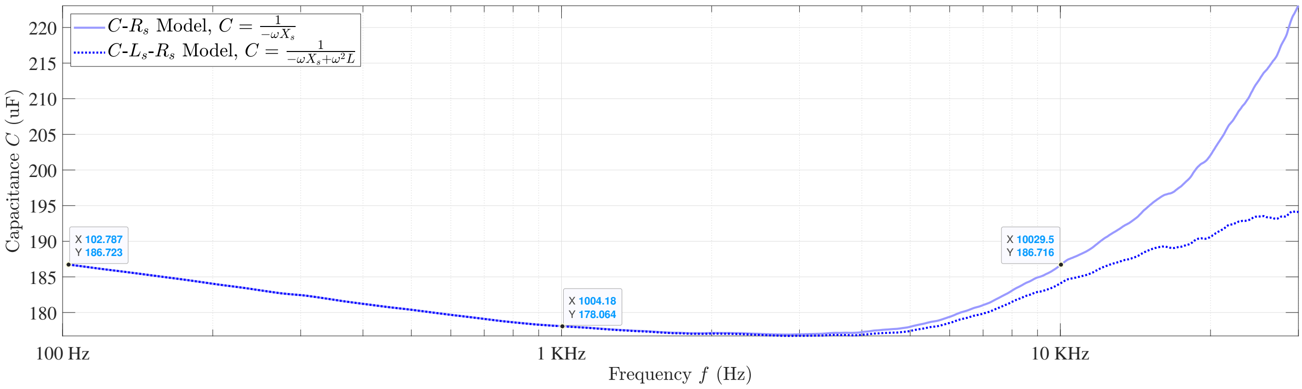


Figure 4.3: Construct the equivalent models of the capacitor

4.3 Tantalum Capacitor (钽电容)

4.4 Ceramic Capacitor (陶瓷电容)

4.5 Monolithic Capacitor (独石电容)

Reference

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[2] IEEE Standard American National Standard Canadian Standard Graphic Symbols for Electrical and Electronics Diagrams (Including Reference Designation Letters). *IEEE Std 315-1975 (Reaffirmed 1993)*, pages i–244, 1993. https://ieeexplore.ieee.org/document/985670.

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