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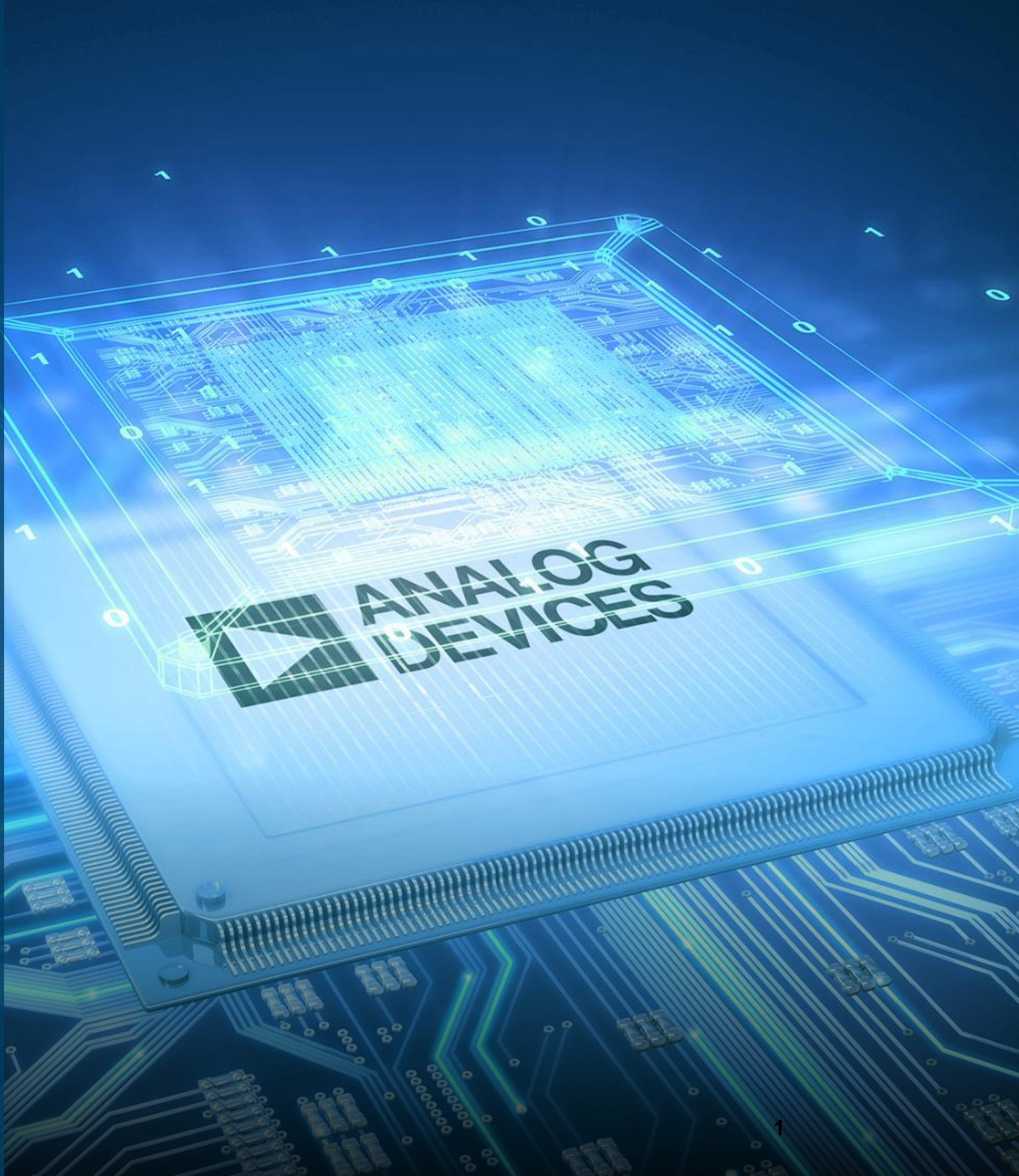
计数电子：
超高灵敏度飞安电流测量

VICKY WONG

应用工程师

精密测量与调理部门

2017/4/27



议题

- 解决客户难题：
  - 问题是什么？
  - 如何解决？
- 设计技术
  - 如何选择器件？
  - 噪声源有哪些？
- 测量挑战
  - 诀窍和考量
- 超高灵敏度飞安电流测量平台
- 光电演示

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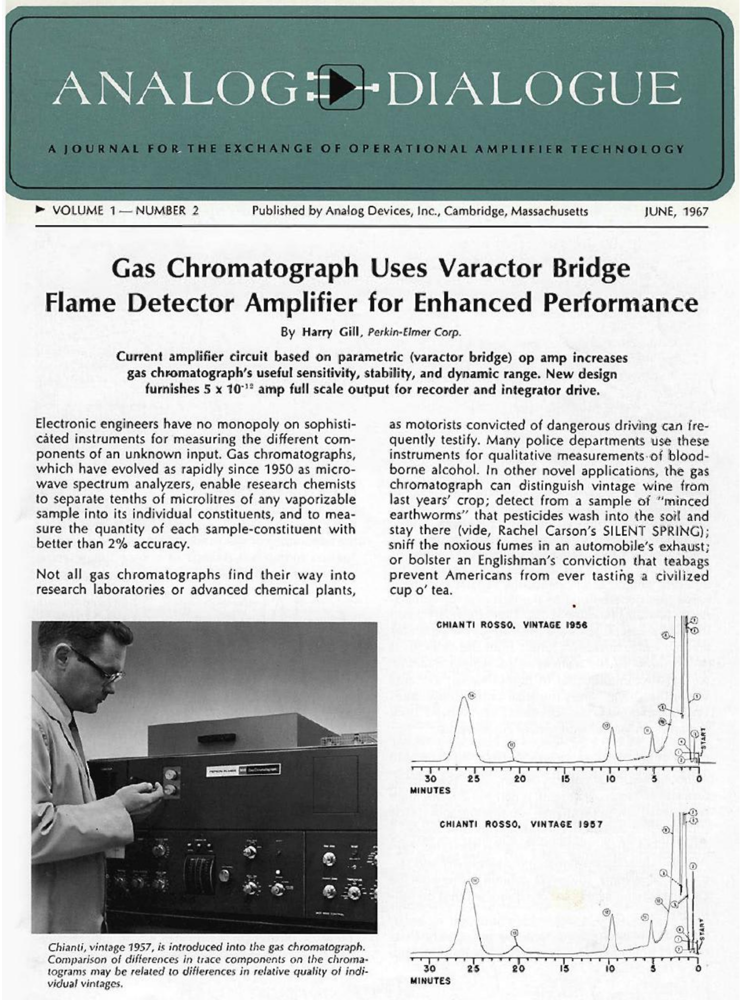
解决客户难题

问题是什么以及如何解决？

跟上不断变化的需求



ANALOG DIALOGUE

A JOURNAL FOR THE EXCHANGE OF OPERATIONAL AMPLIFIER TECHNOLOGY

► VOLUME 1 — NUMBER 2 Published by Analog Devices, Inc., Cambridge, Massachusetts JUNE, 1967

Gas Chromatograph Uses Varactor Bridge Flame Detector Amplifier for Enhanced Performance

By Harry Gill, *Perkin-Elmer Corp.*

Current amplifier circuit based on parametric (varactor bridge) op amp increases gas chromatograph's useful sensitivity, stability, and dynamic range. New design furnishes 5×10^{-12} amp full scale output for recorder and integrator drive.

Electronic engineers have no monopoly on sophisticated instruments for measuring the different components of an unknown input. Gas chromatographs, which have evolved as rapidly since 1950 as microwave spectrum analyzers, enable research chemists to separate tenths of microlitres of any vaporizable sample into its individual constituents, and to measure the quantity of each sample-constituent with better than 2% accuracy.

Not all gas chromatographs find their way into research laboratories or advanced chemical plants, as motorists convicted of dangerous driving can frequently testify. Many police departments use these instruments for qualitative measurements of blood-borne alcohol. In other novel applications, the gas chromatograph can distinguish vintage wine from last years' crop; detect from a sample of "minced earthworms" that pesticides wash into the soil and stay there (vide, Rachel Carson's SILENT SPRING); sniff the noxious fumes in an automobile's exhaust; or bolster an Englishman's conviction that teabags prevent Americans from ever tasting a civilized cup o' tea.

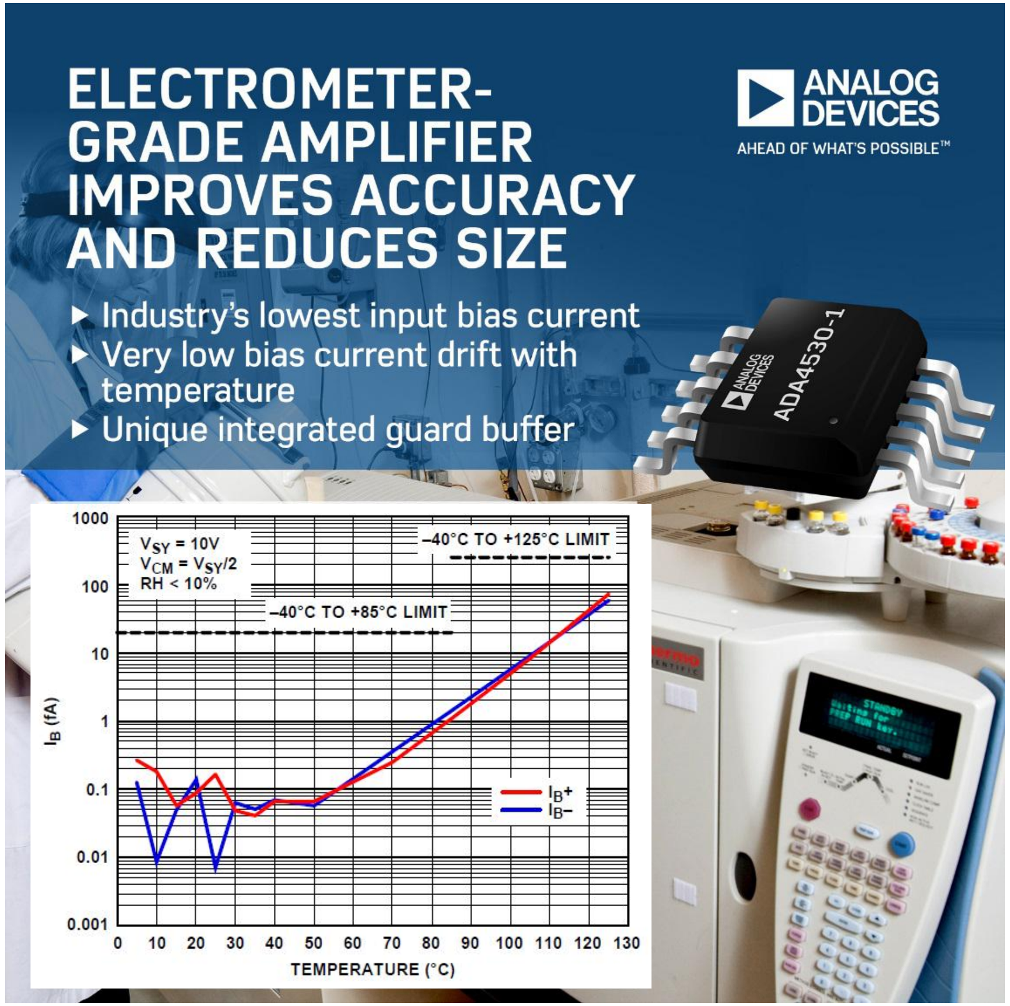
CHIANTI ROSSO, VINTAGE 1956

MINUTES

CHIANTI ROSSO, VINTAGE 1957

MINUTES

Chianti, vintage 1957, is introduced into the gas chromatograph. Comparison of differences in trace components on the chromatograms may be related to differences in relative quality of individual vintages.



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测量仪器需要提高灵敏度

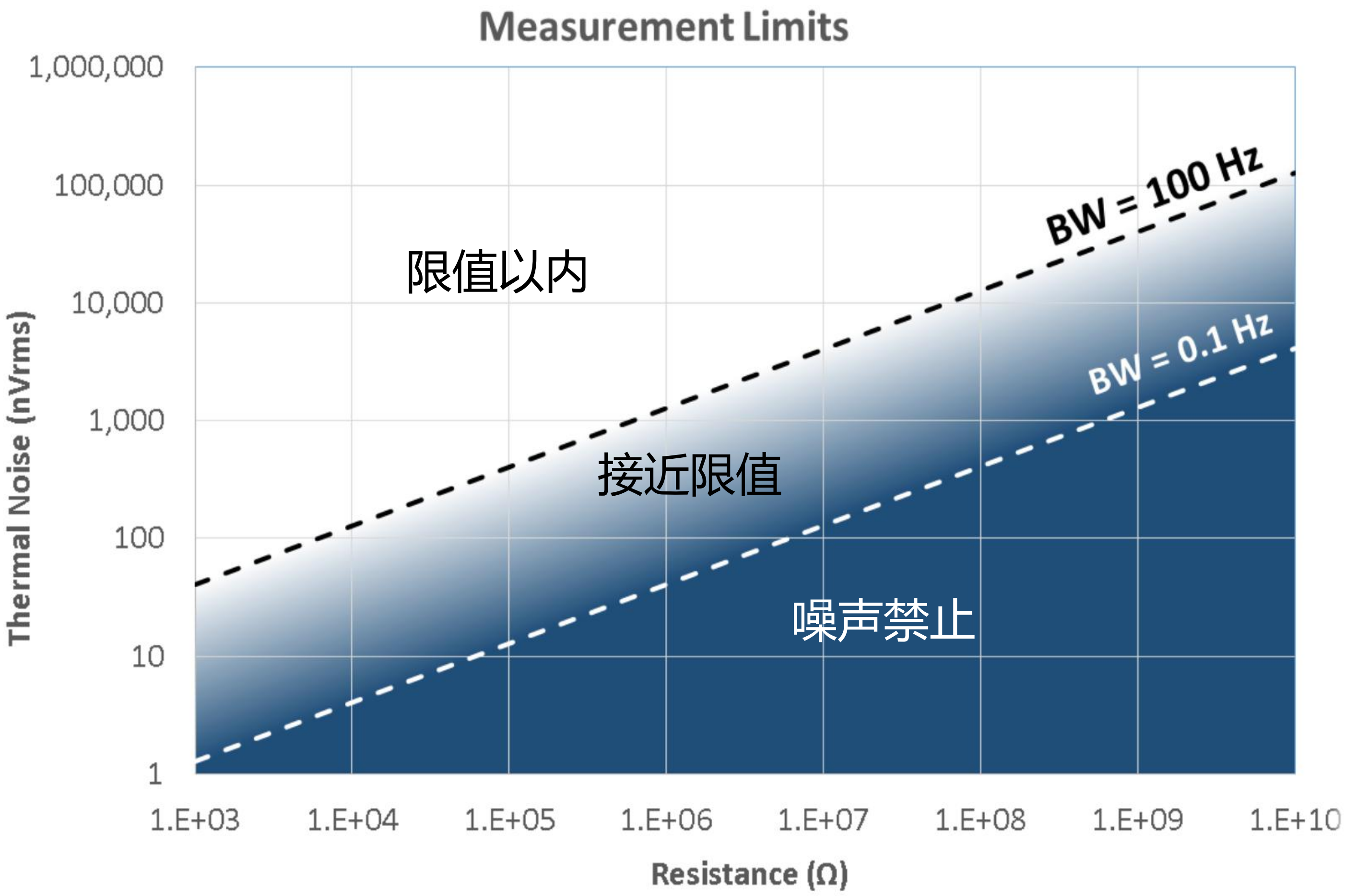
仪器仪表应用

- 化学分析
- 环境计量
- 过程监控

分析测量	超高灵敏度测量系统示例	
分离	HP液相色谱分析 LP液相色谱分析 气相色谱分析	离子色谱分析 快速色谱分析
质谱测定	单一四极式质谱仪 串联四极式质谱仪	飞行时间 FT质谱测定
光谱	UV/Vis 红外、近红外 拉曼光谱 偏振和折光测定 颜色测量 核磁共振	荧光和发光分析 吸收 X射线荧光分析 X射线衍射 感应耦合等离子体 元素分析仪
表面科学	电子显微镜 光学显微镜 表面分析	扫描探针显微镜 共焦显微镜
材料表征	粒子表征 粘度测定和流变测定 量热计	热分析 石油分析仪
电化学	恒电势器 静电计 信号源测量单元 EC传感器	

检测限值

- 测量信号时，测量电平必须高于噪声
- 低电平测量要求我们更靠近阴影区域
- 需要采取特殊措施才能获得精确结果
- 静电计用于低电流测量



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静电计

- 定义：用于测量电荷或电位差的低漏电流电气仪表
- 电压表、电流表、欧姆表、库仑计功能
  - 超高输入阻抗
    （通常在100TΩ以上或高达10PΩ）
  - 超低输入失调电流
    （小于50fA或低至50aA）
  - 采用跨阻放大器
    用于电流测量

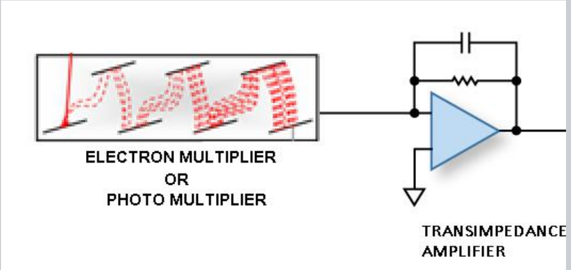
The Prefixes Used with SI Units

Prefix	Symbol	Meaning	Scientific Notation
exa-	E	1,000,000,000,000,000,000	10^{18}
peta-	P	1,000,000,000,000,000	10^{15}
tera-	T	1,000,000,000,000	10^{12}
giga-	G	1,000,000,000	10^{9}
mega-	M	1,000,000	10^{6}
kilo-	k	1,000	10^{3}
hecto-	h	100	10^{2}
deka-	da	10	10^{1}
—	—	1	10^{0}
deci-	d	0.1	10^{-1}
centi-	c	0.01	10^{-2}
milli-	m	0.001	10^{-3}
micro-	μ	0.000 001	10^{-6}
nano-	n	0.000 000 001	10^{-9}
pico-	p	0.000 000 000 001	10^{-12}
femto-	f	0.000 000 000 000 001	10^{-15}
atto-	a	0.000 000 000 000 000 001	10^{-18}

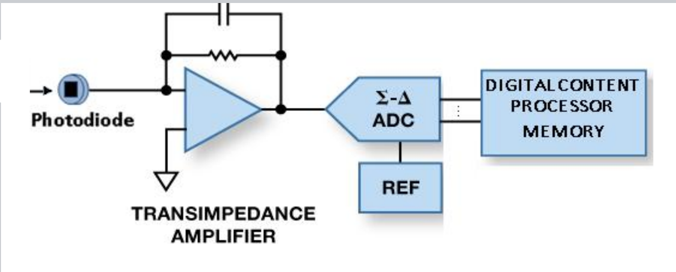
高灵敏度检测器需要精密信号链以支持极低的检测水平

光子/电子检测器：
电流输出

电子或光子乘法器

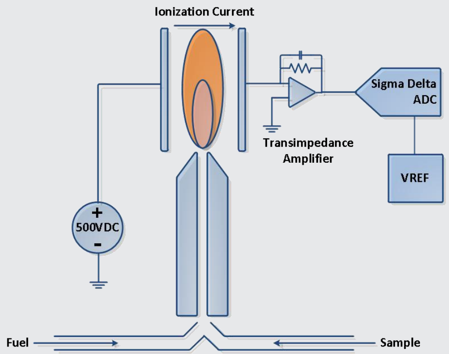


光电二极管

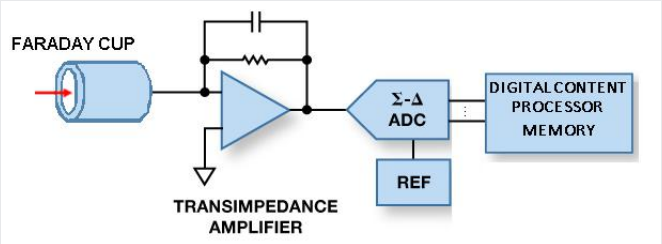


离子检测器：
电荷输出

火焰离子化检测器

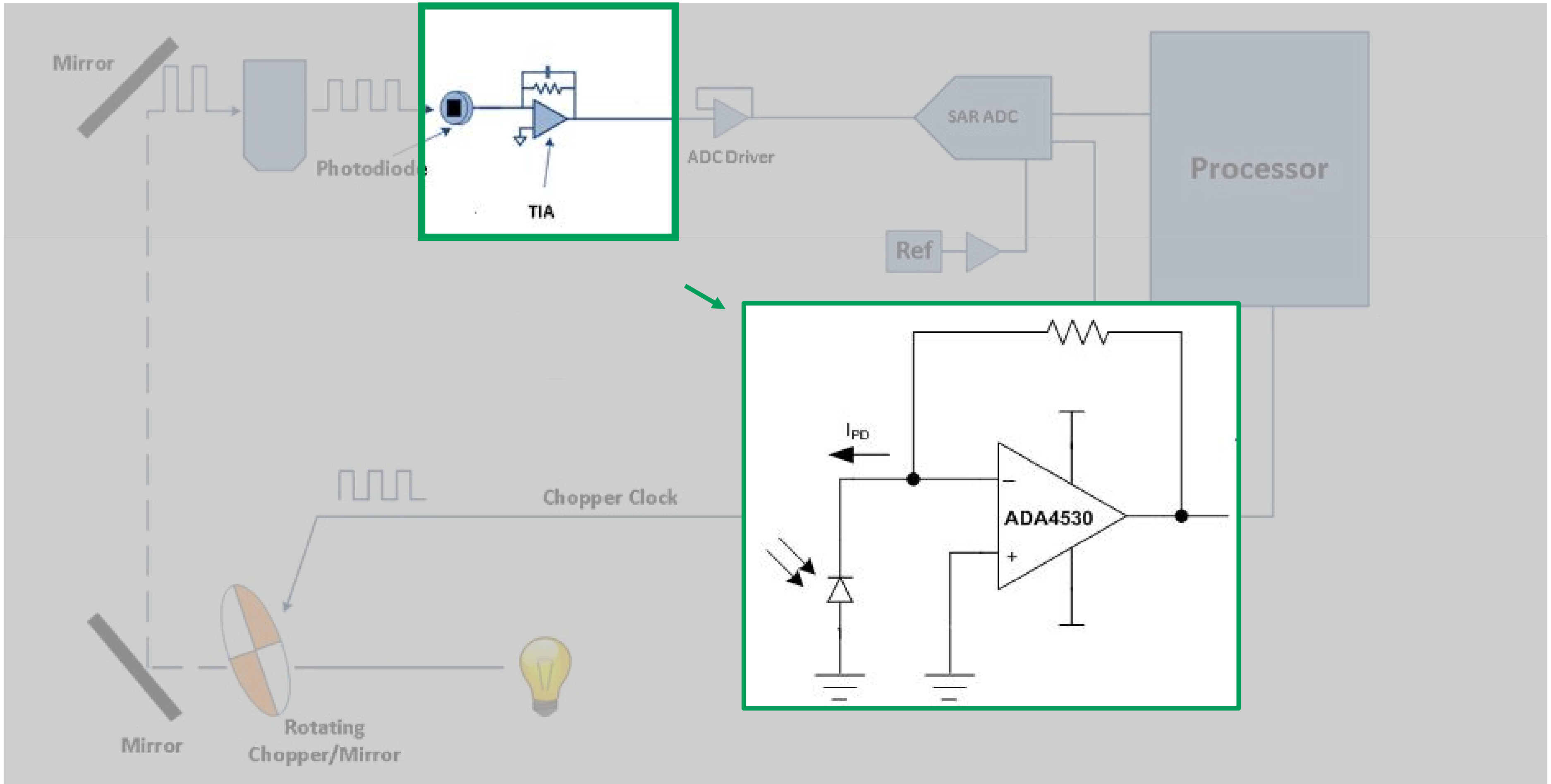


法拉第筒



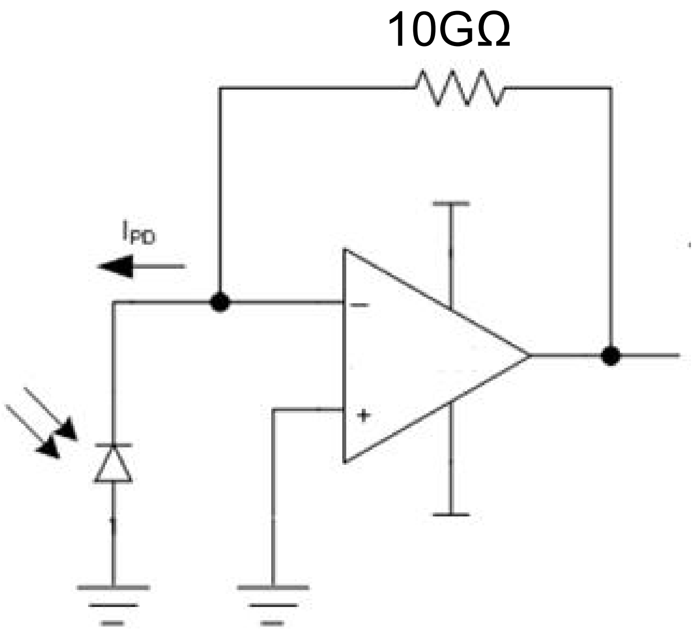
光谱学示例

光谱学：研究物质与放射能之间相互作用的学科
“是什么？”“有多少？”



静电计级放大器需求

- 传感器：
  - 光电二极管（光 → I）
- 运算放大器：
  - 跨阻放大器(TIA)电路(I → V)
- 信号：
  - 所需输出 = 10V
  - 满量程电流 = 1nA
  - R_F = 10GΩ
- 温度：
  - 15C到35C



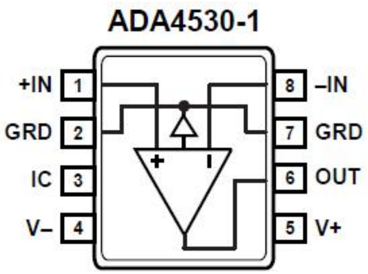
放大器	$I_{BIAS\ MAX}$ @ 25C	Vos最大值 @ 25C	TCVos	1nA误差满量程
ADA4622	10 pA	800 uV	15 uV/C	1.01 %
AD549	100 fA	500 uV	15 uV/C	0.018 %
ADA4530	20 fA	40 uV	0.5 uV/C	0.0025 %

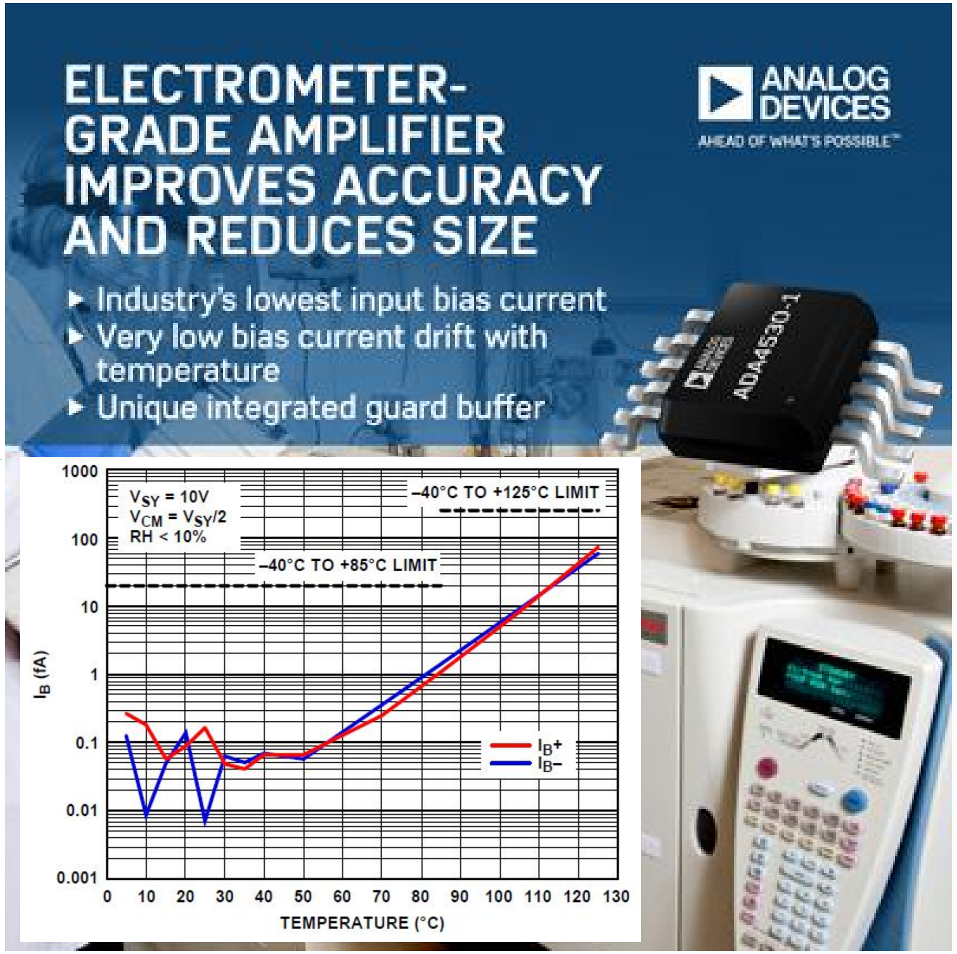
ADA4530-1：不是典型放大器！

主要优势

- 超低输入偏置电流静电计级放大器
- 灵敏度达到新高！
  - 0.1fA典型IB，25C
  - 20fA最大IB，25C至85C
  - 250fA最大IB，125C
  - 低失调漂移：0.5μV/C（最大值）
- 易于使用
  - 集成防护缓冲器
  - 引脚排列针对输入引脚与电源的隔离进行了优化
  - 表贴封装

624个电子/秒！





相比于最好的竞争器件，输入偏置电流低45倍，直流精度提高10倍

ADA4530-1

超越典型测定要求，针对低电流测量

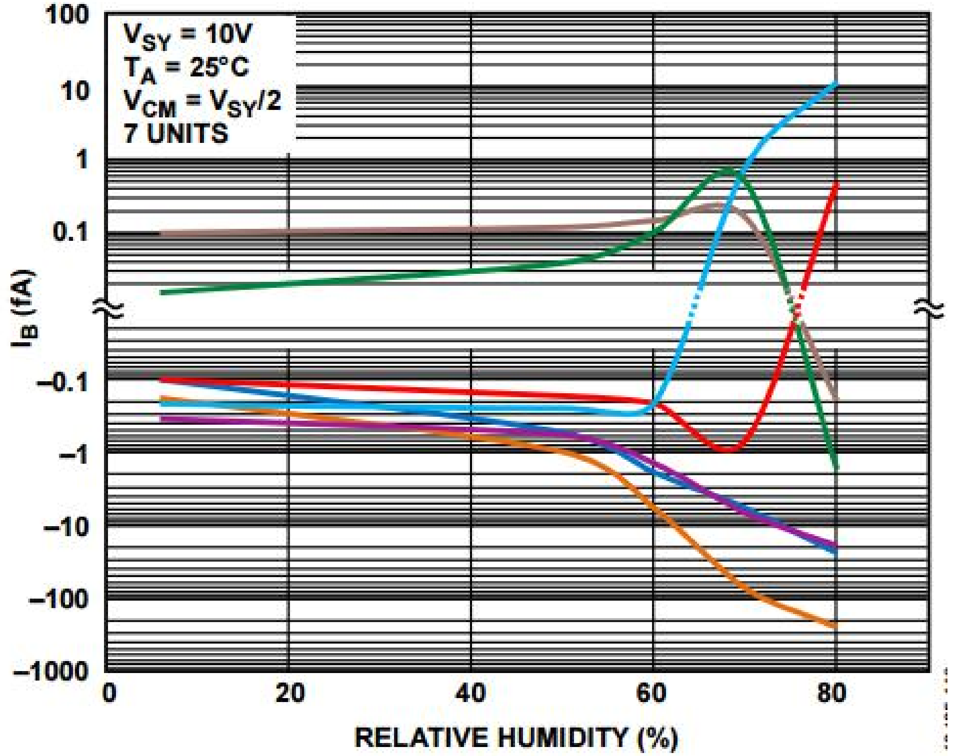


Figure 112. Effective Input Bias Current vs. Relative Humidity

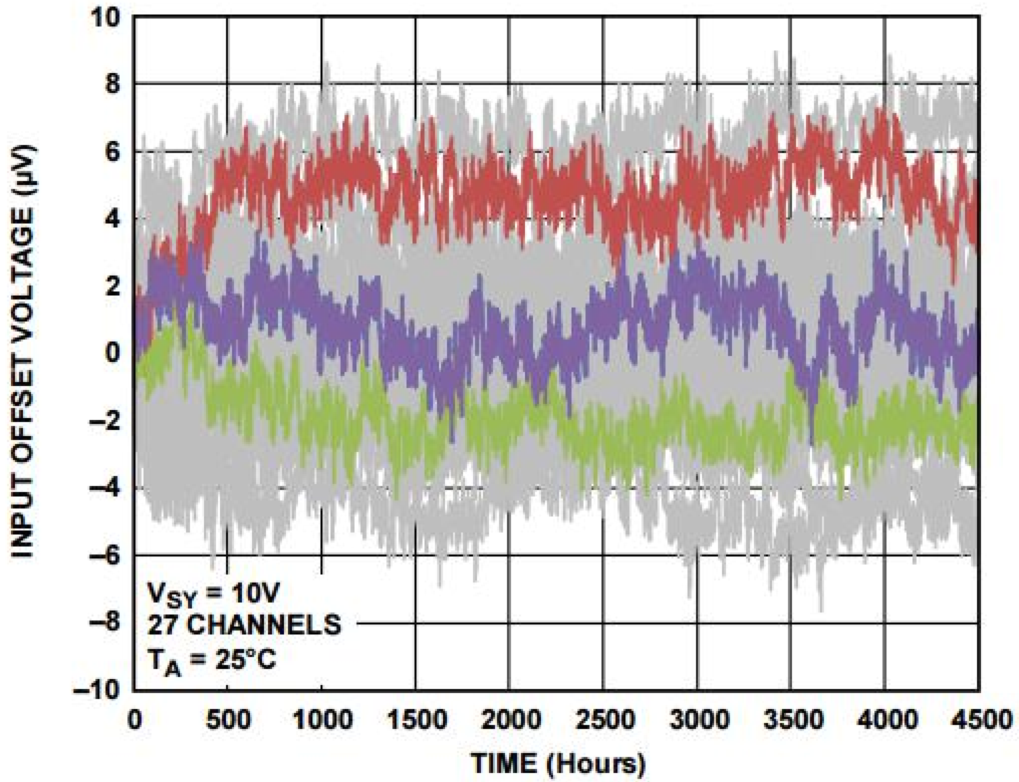


Figure 19. V_{OS} Long-Term Drift

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设计示例

如何选择器件，噪声源有哪些？

实现的挑战

表面污染

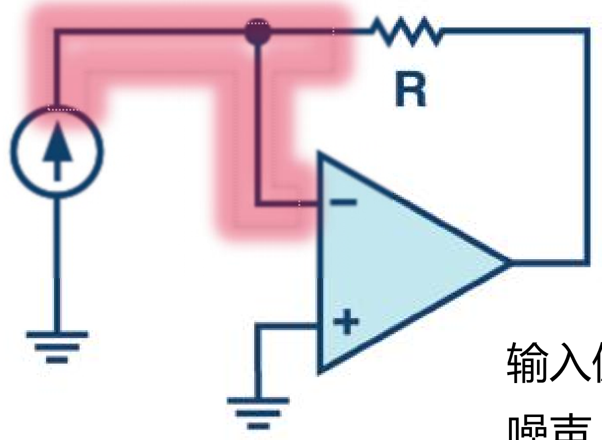
电介质吸收

泄漏

稳定性

湿度

摩擦电



静电耦合

辐射噪声

RF

电力线噪声

输入偏置电流

噪声

失调漂移

输出摆幅

补偿

板用料

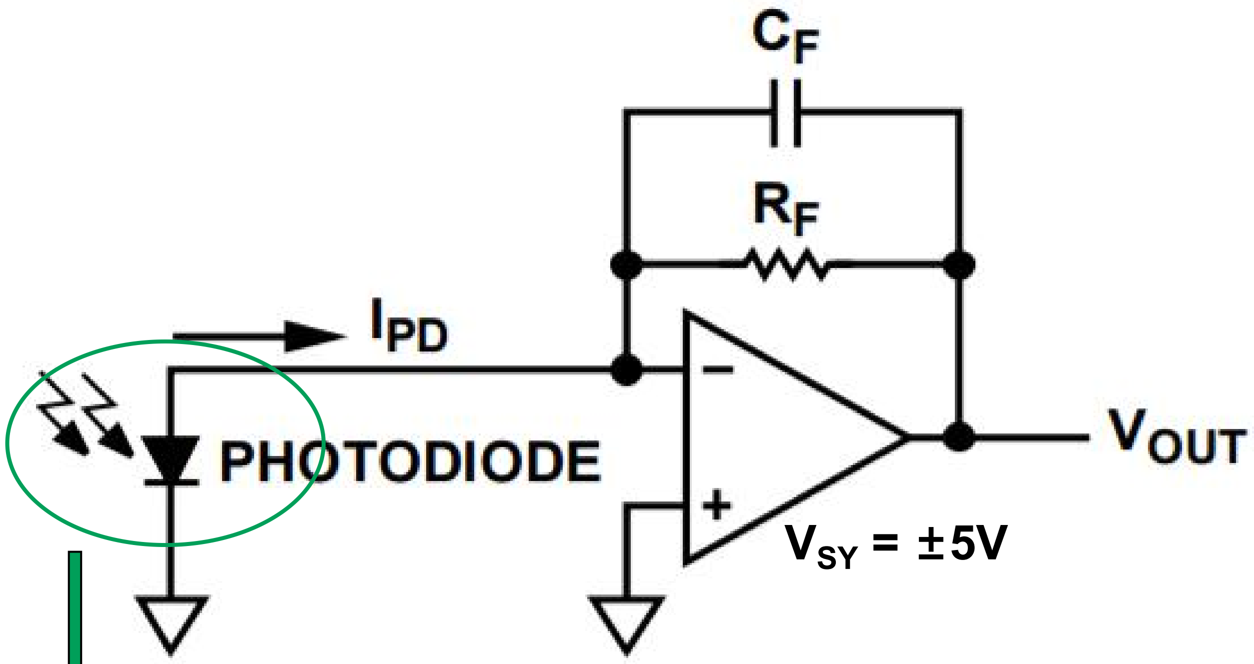
接地噪声

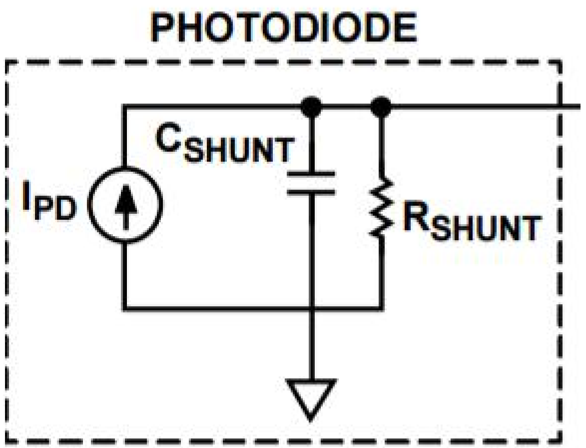
焊膏材料

设计示例

Hamamatsu S1226-18BQ

I_{PD}最大值 = 500pA





- R_{SHUNT} = 50 GΩ典型值，5GΩ最小值
- C_{SHUNT} = 35pF
- 工作温度：-20C到60C

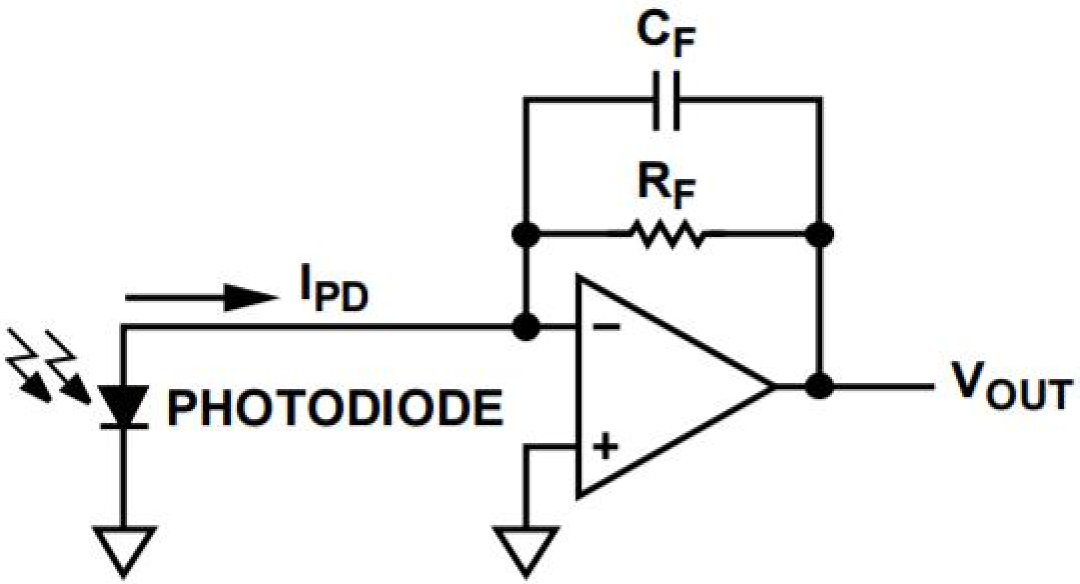
R_F选择

$$RF\ Thermal\ Noise, V_{N,Rf} = \sqrt{4 \times k \times T \times R_F}$$

$$SNR = \frac{V_{OUT}}{V_{N,Rf}}$$

$$SNR\ \alpha\ \sqrt{R_F}$$

SNR改善$\sqrt{R_F}$



R_F选择

限制R_{SHUNT}上限的因素

- 最大输出摆幅

$$V_{OUT} = I_{PD} \times R_F$$

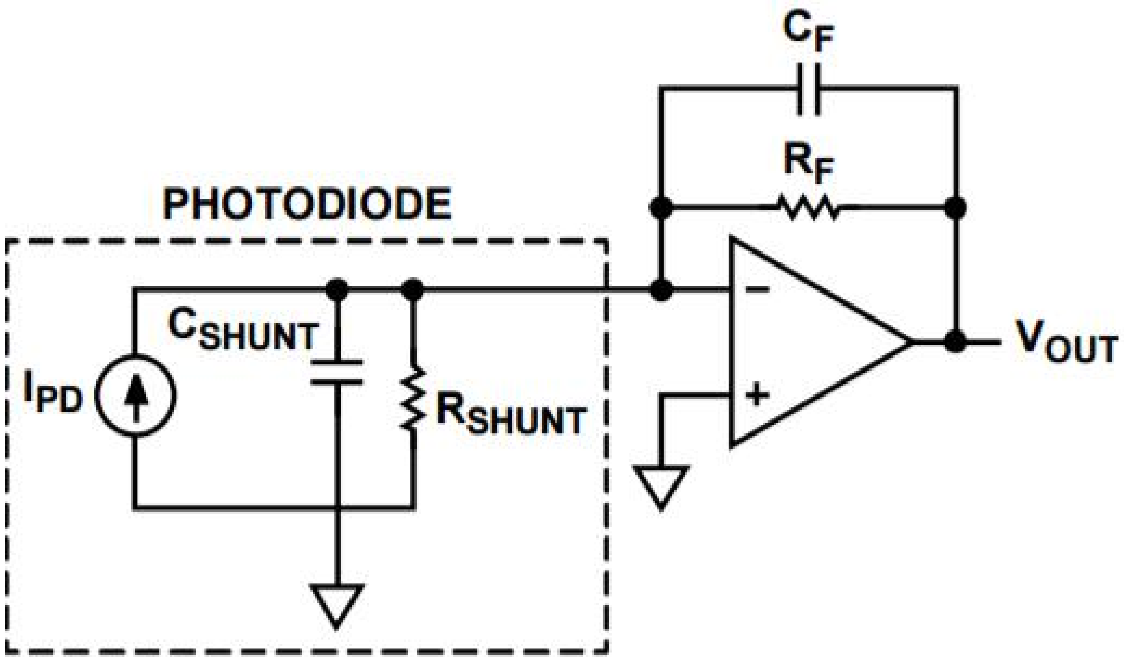
- 信号带宽

$$f_{SIGNAL} = \frac{1}{2\pi R_F C_F}$$

- R_{SHUNT}
  - R_{SHUNT}随温度提高而降低

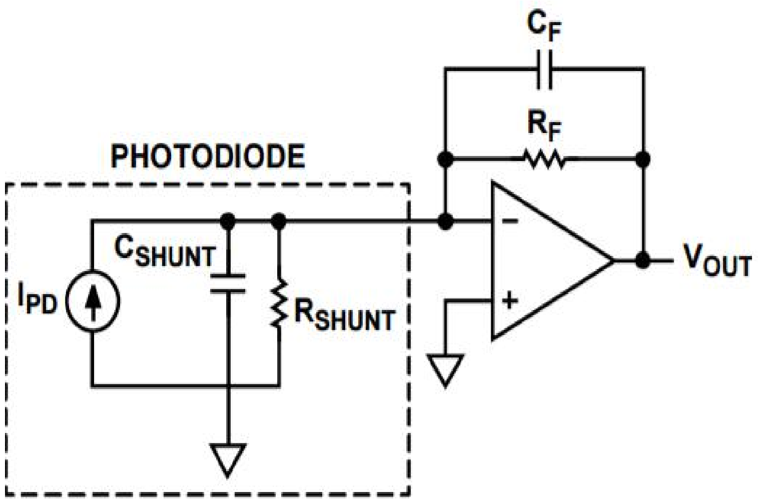
$$Noise\ Gain\ @\ DC = 1 + \frac{R_F}{R_{SHUNT}}$$

- 电流噪声
  - 放大器电流噪声 > R_F热噪声



直流误差预算

误差源	公式	ADA4530-1	
		25 C	60C
R_{SHUNT}		5 GΩ	442 MΩ
V_{OS}		40 uV	40 uV + 18 uV
噪声增益	$1+\frac{R_F}{R_{SHUNT}}$	3	23
Vos误差RTO	$V_{OS} \times Noise\ Gain$	120 uV	1.3 mV
I_B		20 fA	20 fA
I_B误差RTO	$I_B \times R_F$	200 uV	200 uV
总误差RTO		320 uV	1.5 mV
总误差RTI		**32 fA**	**150 fA**



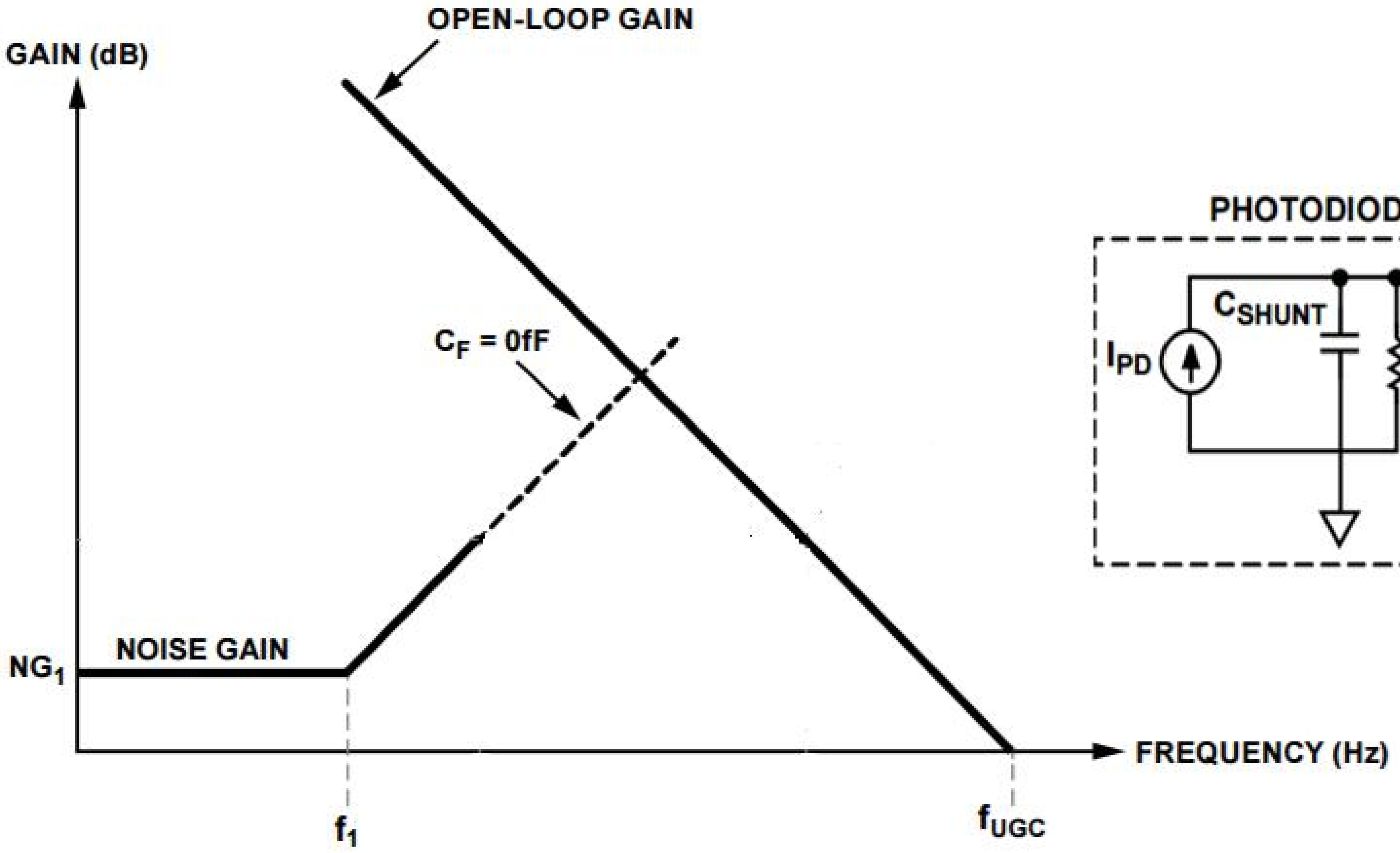
RTO：折合到输出端
RTI：折合到输入端

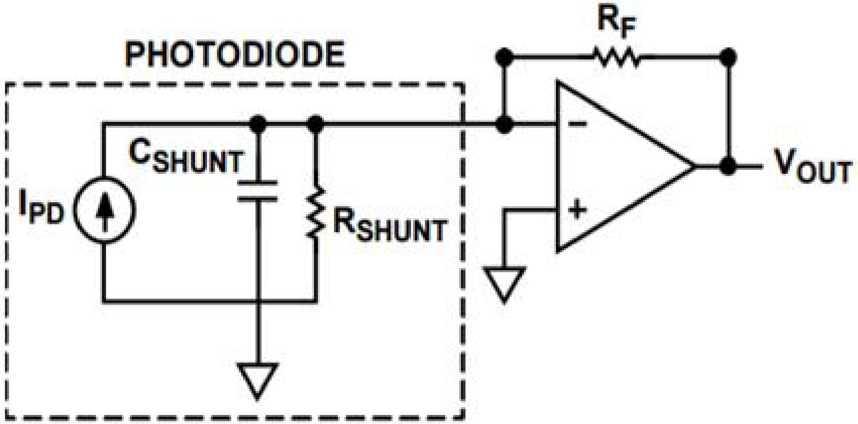
直流误差预算

误差源	公式	ADA4530-1		竞争产品A	
		25 C	**60C**	**25 C**	**60C**
R_{SHUNT}		5 GΩ	442 MΩ	5 GΩ	442 MΩ
V_{OS}		40 uV	40 uV + 18 uV	150 uV	150 uV + 140 uV
噪声增益	$1+\frac{R_F}{R_{SHUNT}}$	3	23	3	23
Vos误差RTO	$V_{OS} \times Noise\ Gain$	120 uV	1.3 mV	450 uV	6.8 mV
I_B		20 fA	20 fA	20 fA	220 fA
I_B**误差RTO**	$I_B \times R_F$	200 uV	200 uV	200 uV	2.2 mV
总误差RTO		320 uV	1.5 mV	320 uV	9 mV
总误差RTI		**32 fA**	**150 fA**	**65 fA**	**900 fA**

RTO：折合到输出端
RTI：折合到输入端

交流性能





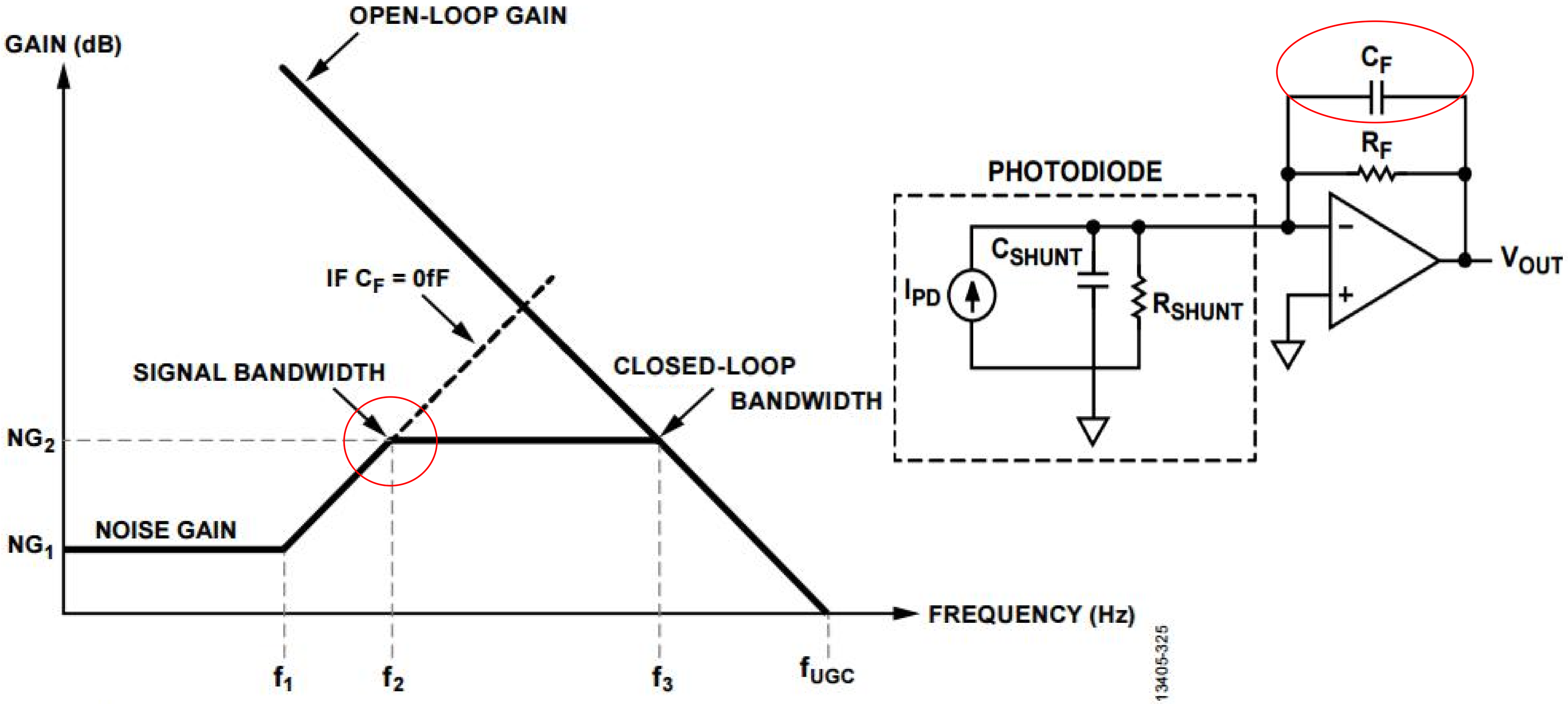
$$NG_1 = 1 + \frac{RF}{R_{SHUNT}}$$

$$f_1 = \frac{1}{\frac{R_F R_{SHUNT}}{R_F + R_{SHUNT}}\left(C_F + C_{SHUNT}\right)}$$

交流性能

$$NG_2 = 1 + \frac{C_{SHUNT}}{C_F}$$

$$NG_1 = 1 + \frac{RF}{R_{SHUNT}}$$



$$f_1 = \frac{1}{\frac{R_F R_{SHUNT}}{R_F + R_{SHUNT}}\left(C_F + C_{SHUNT}\right)}$$

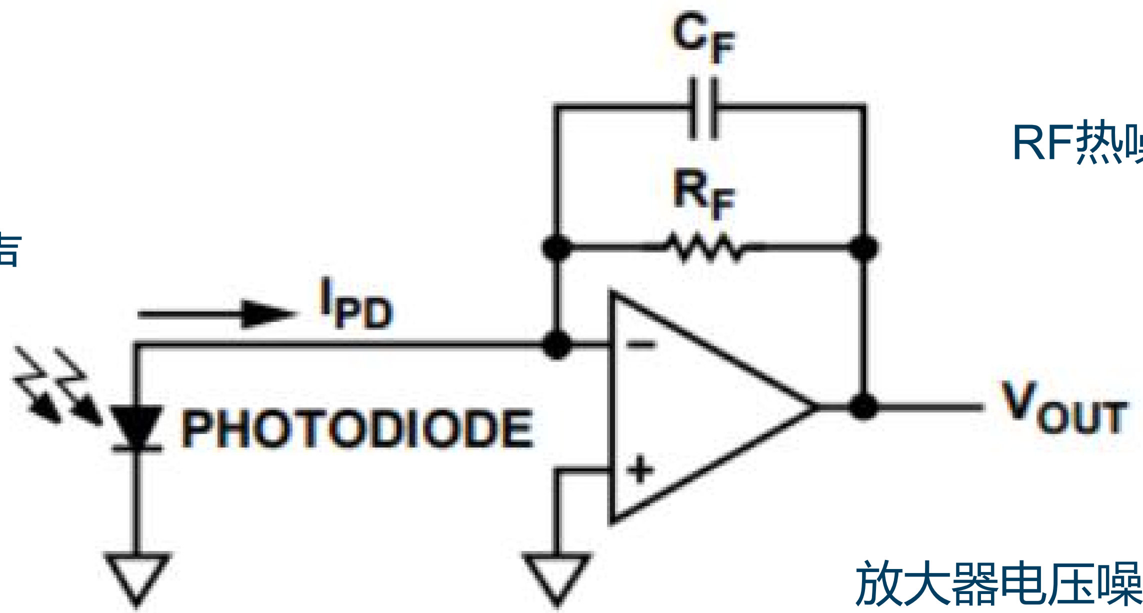
$$f_2 = \frac{1}{R_F C_F}$$

$$f_3 = \frac{f_{UGC}}{\left(1 + \frac{C_{SHUNT}}{C_F}\right)}$$

噪声源

光电二极管噪声

RF热噪声



放大器电压噪声

放大器电流噪声

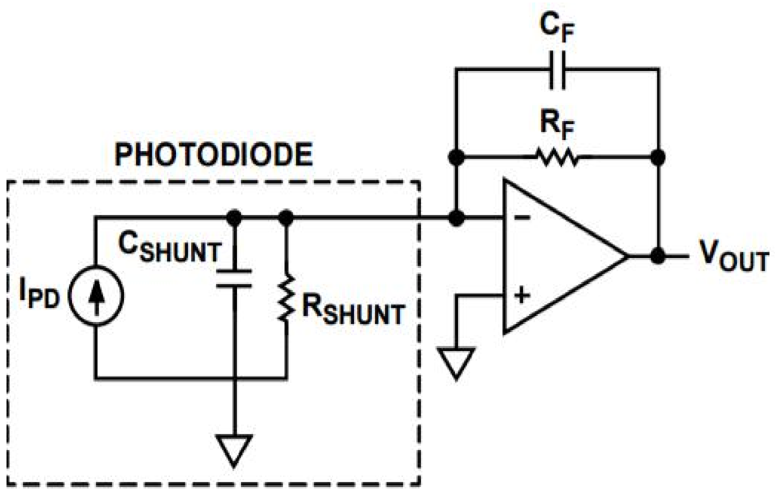
低频噪声

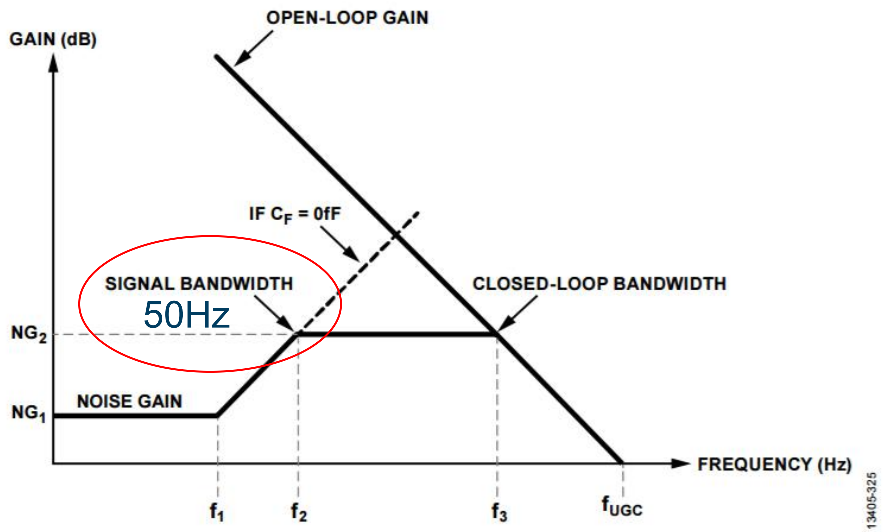
噪声源	RTO噪声公式	噪声带宽	RTO噪声 @ 25C	RTO噪声 @ 60C
R_F	$\sqrt{4\,k\,TR_F}$	$\frac{\pi}{2}\,f_2$	12.8 uV/rtHz	13.5uV/rtHz
R_{SHUNT}（光电二极管）	$\frac{R_F}{R_{SHUNT}}\sqrt{4\,k\,TR_{SHUNT}}$	$\frac{\pi}{2}\,f_2$	18 uV/rtHz	64uV/rtHz
放大器电流噪声	$I_N\,R_F$	$\frac{\pi}{2}\,f_2$	700 nV/rtHz	2.4 uV/rtHz
总低频噪声(NSD)			22 uV/rtHz	66 uV/rtHz
总低频噪声(RMS)			195 uVrms	585 uVrms

注：

$$f_2 = \frac{1}{R_F C_F} = 50\text{Hz}$$

* NSD：噪声谱密度



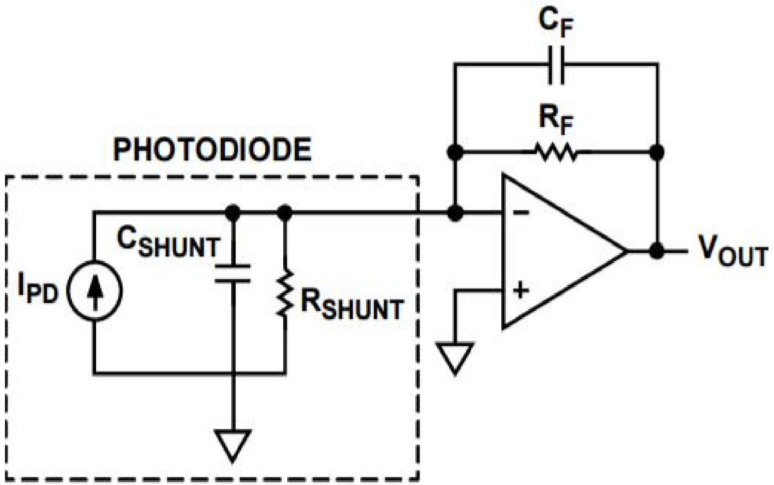


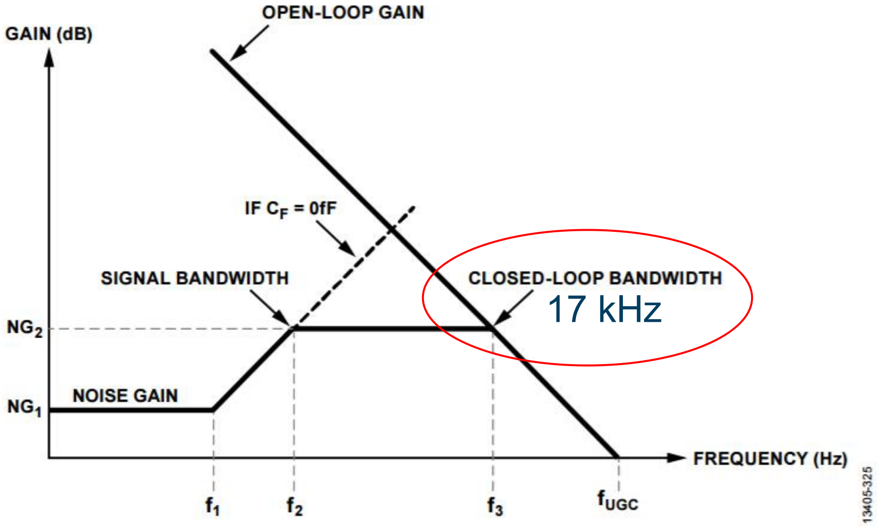
高频噪声

噪声源	RTO噪声公式	噪声带宽	RTO噪声 @ 25C	RTO噪声 @ 60C
放大器电压噪声	$V_N \times (1+\frac{C_{SHUNT}}{C_F})$	$\frac{\pi}{2} f_3$	1.6 uV/rtHz	1.7 uV/rtHz
总高频噪声			271 uVrms	286 uVrms

注：

$$f_3 = \frac{f_{UGC}}{\left(1+\frac{C_{SHUNT}}{C_F}\right)} = 17\ \text{kHz}$$





噪声小结

噪声源	RTO噪声公式	噪声带宽	RTO噪声 @ 25C	RTO噪声 @ 60C
R_F	$\sqrt{4kTR_F}$	$\frac{\pi}{2}f_2$	12.8 uV/rtHz	13.5uV/rtHz
R_{SHUNT}（光电二极管）	$\frac{R_F}{R_{SHUNT}}\sqrt{4kTR_{SHUNT}}$	$\frac{\pi}{2}f_2$	18 uV/rtHz	64uV/rtHz
放大器电流噪声	$I_N R_F$	$\frac{\pi}{2}f_2$	700 nV/rtHz	2.4 uV/rtHz
放大器电压噪声	$V_N \times (1+\frac{C_{SHUNT}}{C_F})$	$\frac{\pi}{2}f_3$	1.6 uV/rtHz	1.7 uV/rtHz
总低频噪声(RMS)			195 uVrms	585 uVrms
总高频噪声（由于V_N）			271 uVrms	286 uVrms

注：
f_2 = 信号带宽 = 50Hz
f_3 = 闭环带宽 = 17 kHz

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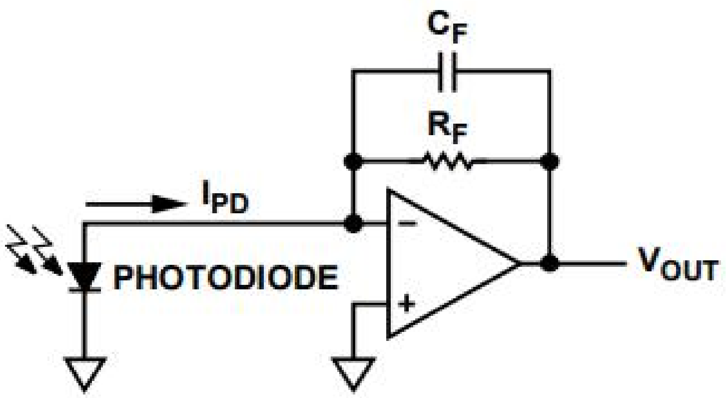
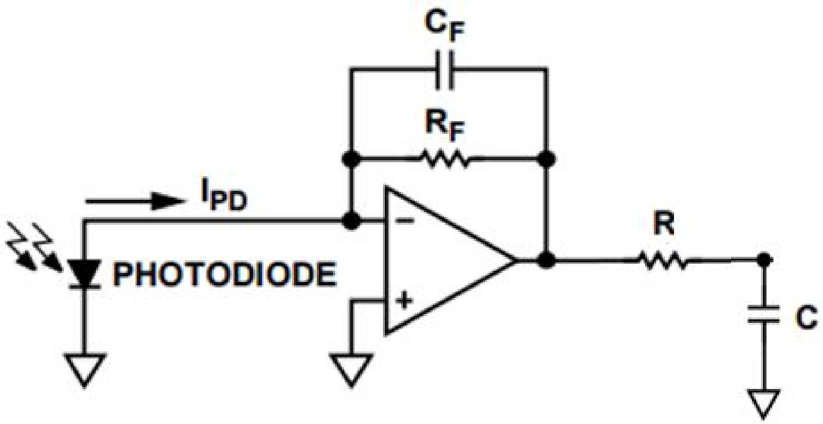
信噪比

	无后置LPF	有后置LPF
低频噪声	195 μVrms	195 μVrms
高频噪声	271 μVrms	46 μVrms
总噪声	333 μVrms	200 μVrms
SNR	89.5 dB	94 dB



无LPF



有LPF

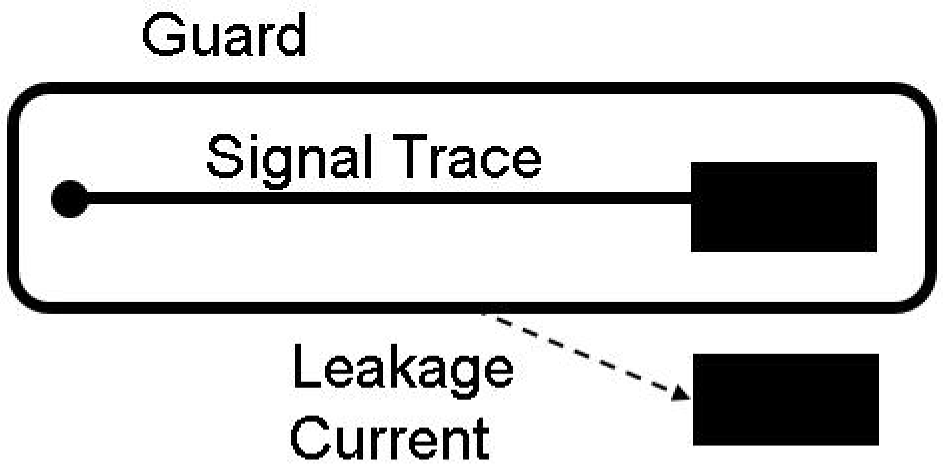
F_{FILTER} = 500Hz

测量挑战

诀窍和考量

保护

- 用另一导体将高阻抗节点的绝缘体包围起来，并将导体驱动到保护电压（等于或接近高阻抗节点电位）
- 更好的布局产生更好的性能，性能随时间和环境条件的变化越小



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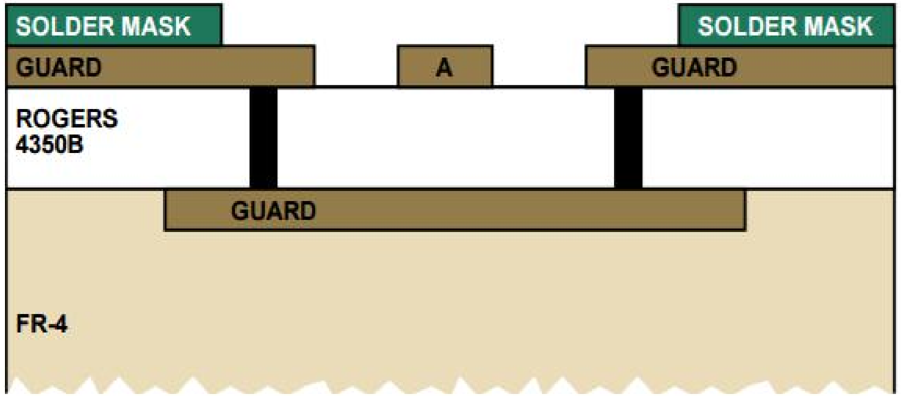
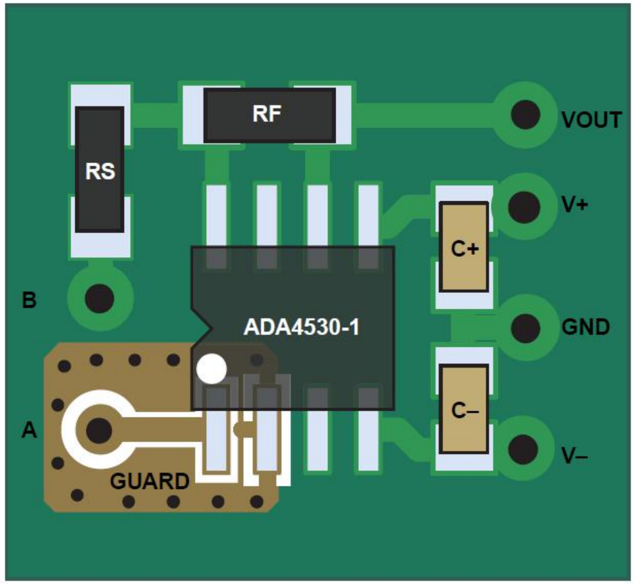
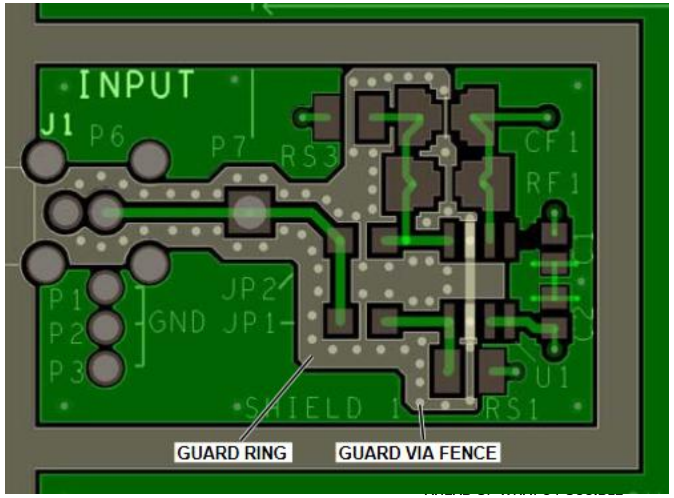
保护

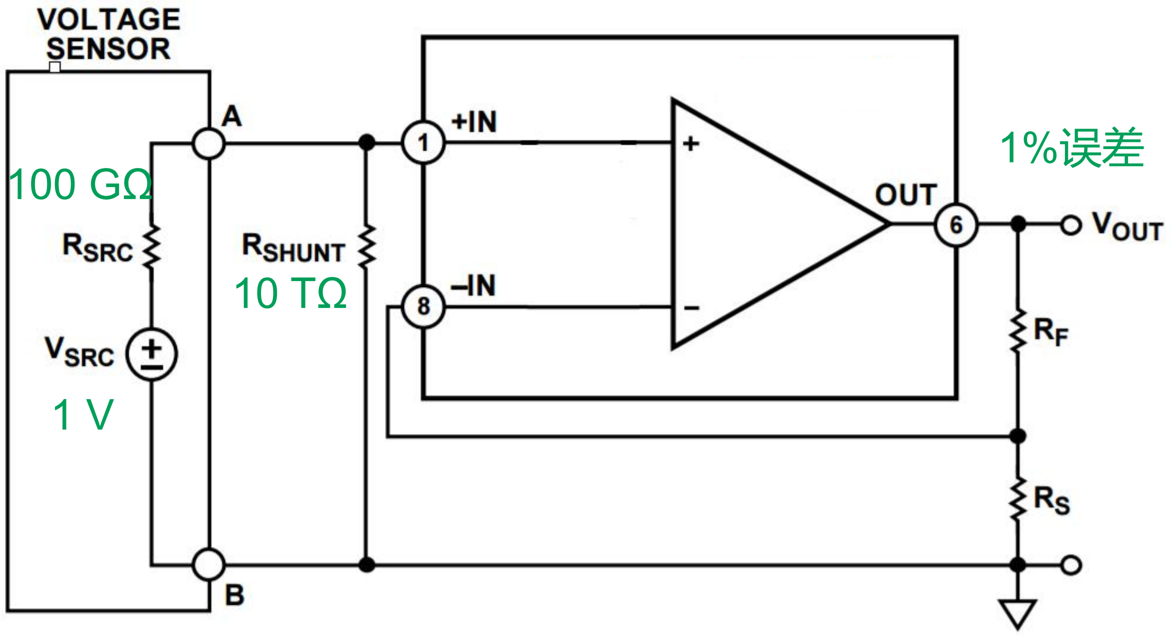
- 保护环
  - 保护表面泄漏
  - 去除保护环/走线上的焊罩/丝网
    - 避免吸潮
  - 需要由与输入端等电位的放大器（如缓冲器）驱动
- 保护层
  - 保护PCB主体
- 过孔防护
  - 保护侧面漏电流路径

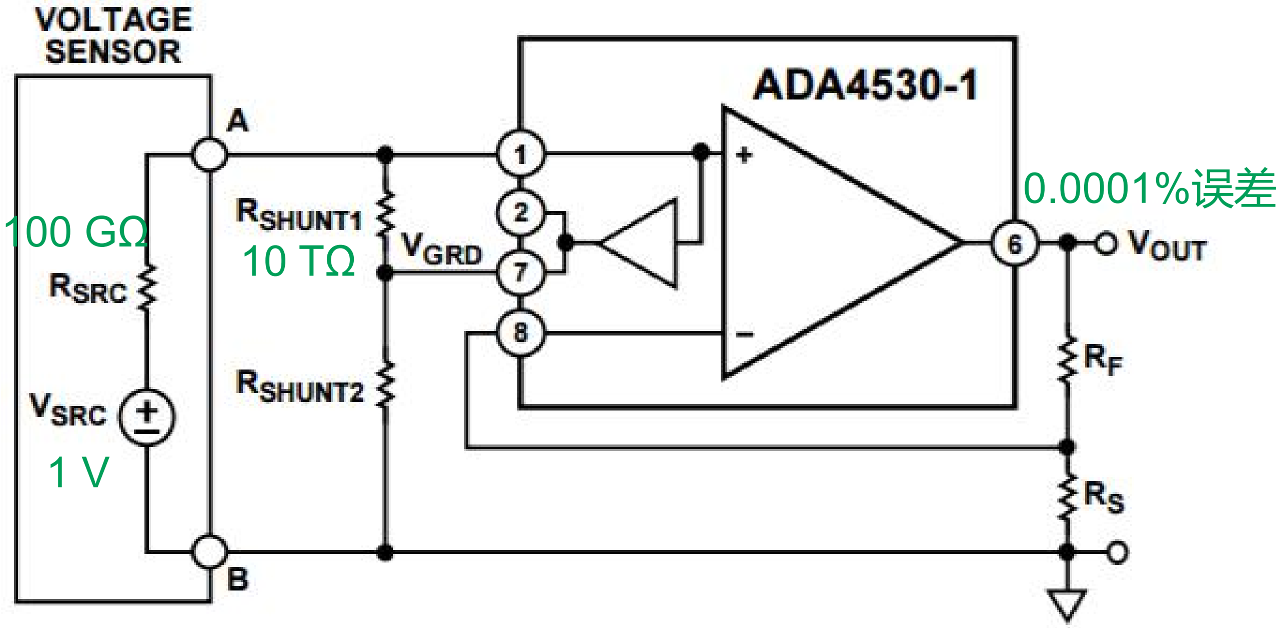






保护示例

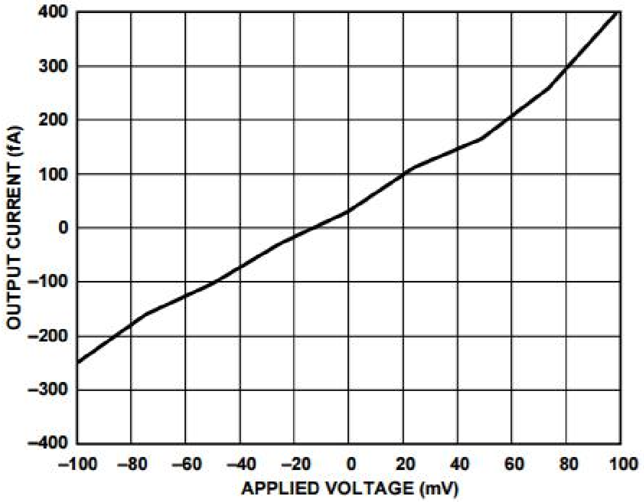

VOLTAGE SENSOR
A
B
100 GΩ
RSRC
VSRC
1 V
RSHUNT
10 TΩ
+IN
–IN
1
8
6
+
–
OUT
1%误差
VOUT
RF
RS


VOLTAGE SENSOR
A
B
100 GΩ
RSRC
VSRC
1 V
RSHUNT1
10 TΩ
RSHUNT2
VGRD
ADA4530-1
1
2
7
8
6
+
–
0.0001%误差
VOUT
RF
RS

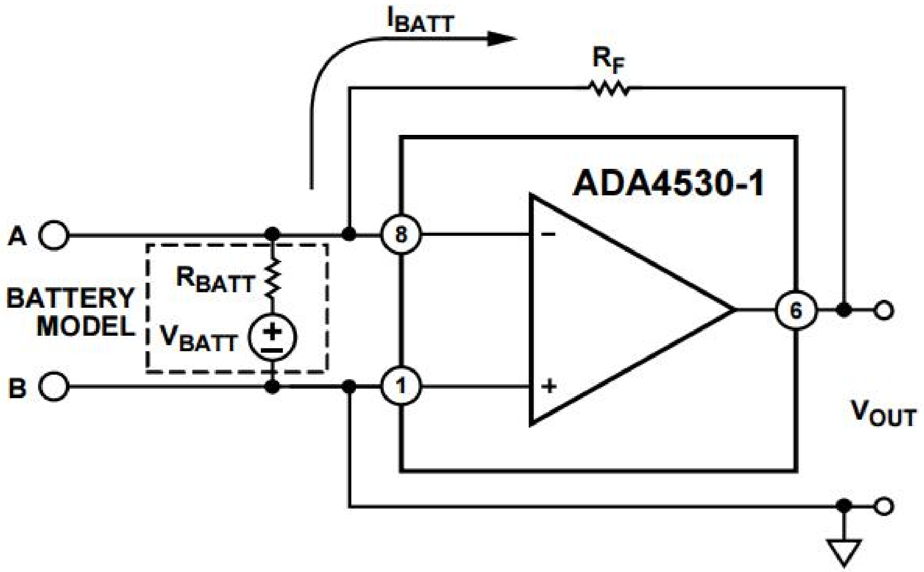
污染

污染源形成弱电池

- 焊剂残留
- 尘土和其他颗粒状堆积
- 灰尘
- 体油
- 含盐潮气



受RMA污染的绝缘层的电流对电压响应
V_{BATT} = 15mV
R_{BATT} = 300 GΩ



清洁和搬运像电路设计本身一样重要！

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污染

- 装配后建议清洗/清洁
- 潮气会降低PCB和电缆的绝缘性
  - 选择合适的材料并在受控环境中测量
  - 清洗后烘烤以消除吸收的湿气
- 不要使用免清洁型焊膏

材料	吸湿性(%)
优先选择FR-4	0.50
高纯度PTFE	0.02

资料来源：Rogers Corp.

Table 7. Recommended Cleaning Procedures for Different Solder Paste Material

Solder Paste Type	Solder Paste Part Number	Recommended Cleaning Procedure[1]
RMA	AIM RMA258-15R	15 min clean time in an ultrasonic cleaner with fresh IPA, followed by 1.5 hours of bake time at 125°C
Water Soluble	SAC305 Shenmao	1.5 hours clean time in an ultrasonic cleaner with fresh IPA, followed by 1.5 hours of bake time at 125°C
No Clean	SAC 305 AMTECH LF4300	3 hours clean time in an ultrasonic cleaner with fresh IPA, followed by 3 hours of bake time at 125°C

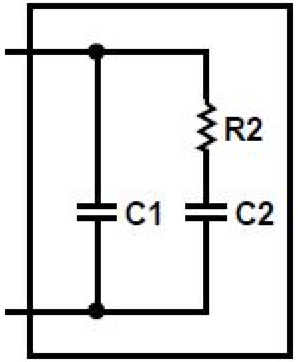
[1] Bake time was not optimized and was set equal to the cleaning time.

- UG-865介绍了高效清洁程序

电介质吸收

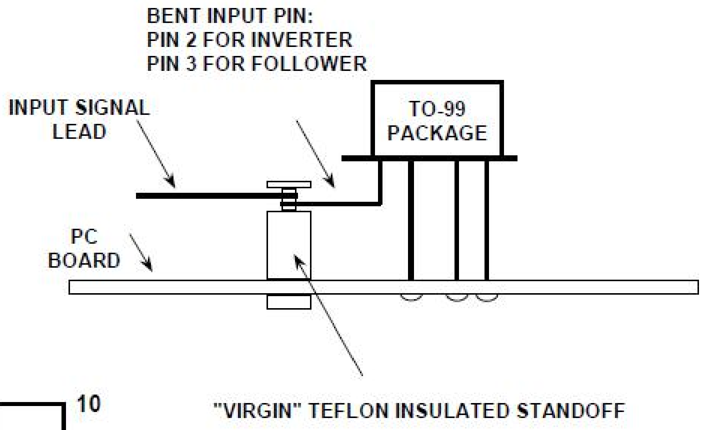
- 介电弛豫/浸润
- 响应电场而发生极化，介电弛豫是指这种极化有所延迟的现象
- 以下对象中常见：
  - 电容
  - 多层PCB
- 其模型常常是一个RC与“理想”电容并联
- 在静电计电路中，它是建立时间的主要部分

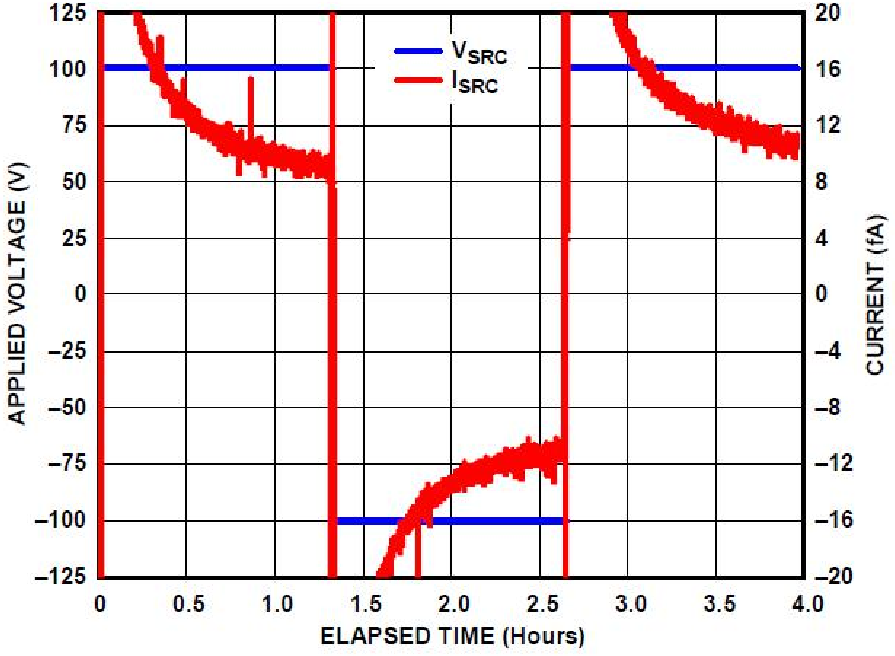
INSULATOR
MODEL



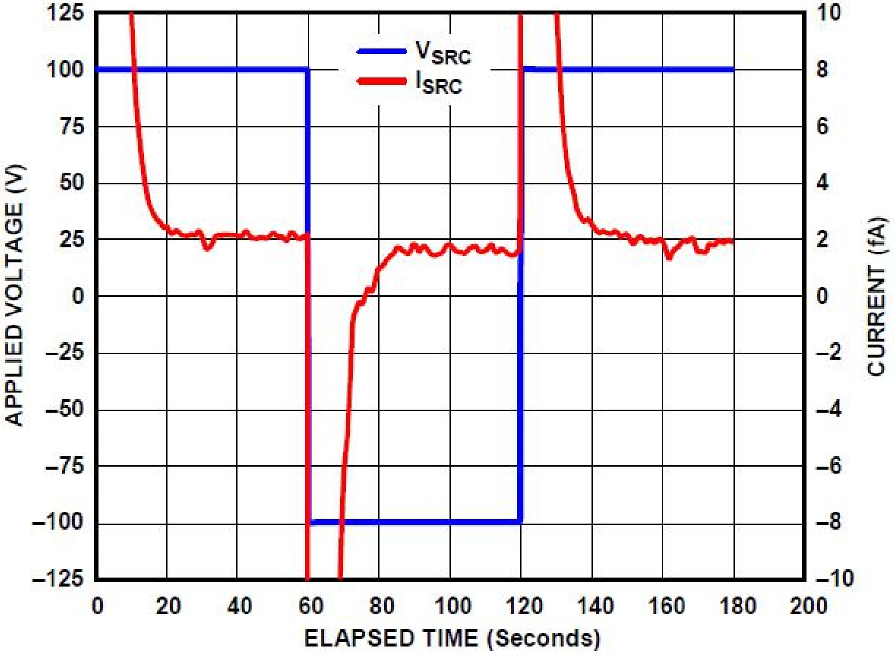
处理PCB中的电介质吸收

- PTFE、Rogers 4350B





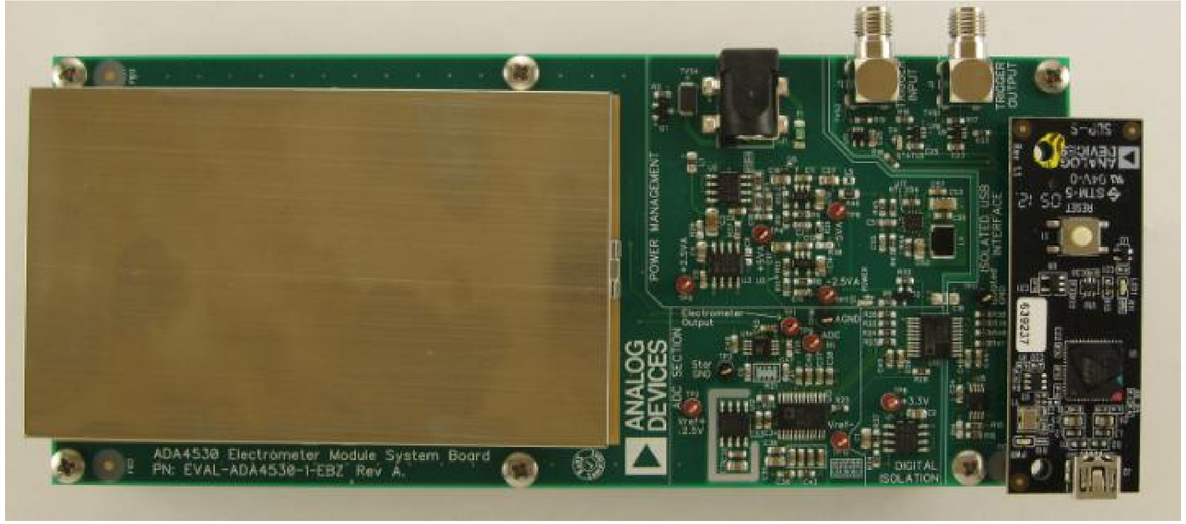
玻璃环氧树脂(FR-4)



Rogers 4350B

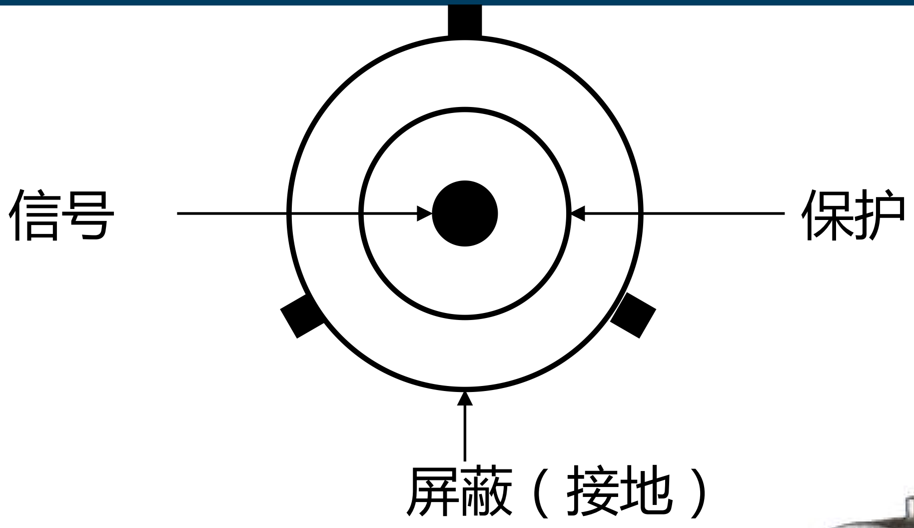
屏蔽

- 屏蔽有助于让杂散场远离敏感节点
- 操作员能接触到的屏蔽应接地以确保安全



电缆和连接器

- 最佳：使用三同轴电缆
  - 有一根额外的内部导线来保护信号
- 只要中心导线与屏蔽体之间的电位差非常小，BNC、SMA和同轴电缆是可行的
  - 经济高效
  - 某些RF材料(PTFE)具有良好的低漏电、低DA属性
- 捆扎电缆以减少摩擦起电效应



总结

- 设计低电流测量硬件需要关注很多细节！

问题	来源	解决方案
PCB泄漏	湿气和污染	灰尘覆盖/屏蔽
	焊剂污染	不要使用免清洁型焊膏；清洗和烘烤
电介质吸收	电荷陷入电介质中	使用PTFE / Rogers 4350B电介质材料
电缆泄漏	导体之间的绝缘质量很差	使用PTFE绝缘电缆或三同轴电缆/连接器
外部噪声	电磁场、电力线干扰	屏蔽和保护
	机械振动、摩擦起电	捆扎电缆

- 飞安电流测量平台解决了许多问题，支持快速开发原型

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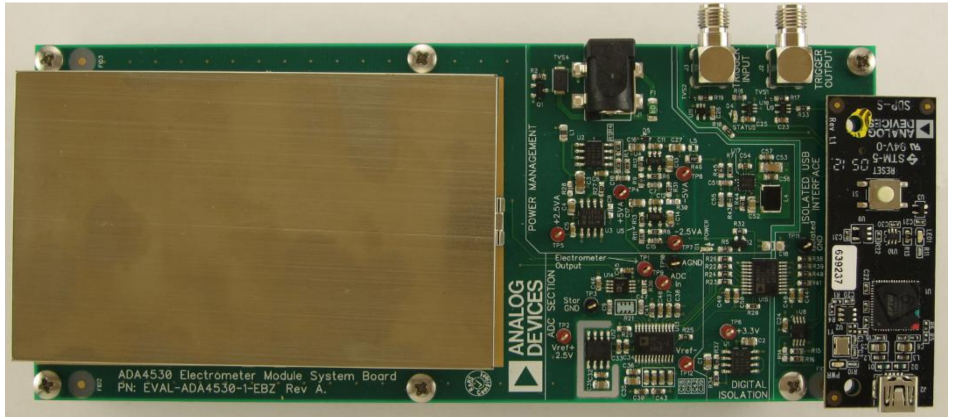
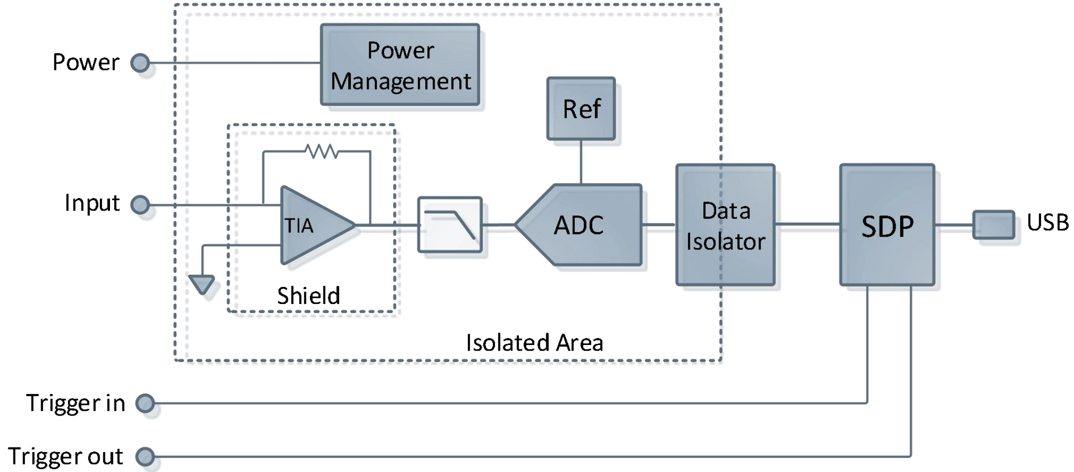
飞安电流测量平台

轻松导入设计

超高灵敏度飞安计模块

- 针对低电流输出传感器的开发模块
  - 通过SMA连接器与光电二极管、法拉第筒等传感器直接连接
- 特性
  - **<10fA灵敏度**，10GΩ跨阻
    - 500pA测量范围
    - 屏蔽
    - 利用**ADuM3151**隔离
  - 飞安输入偏置运算放大器
    - **ADA4530-1**
  - 24位分辨率ADC
    - **AD7172-2**
  - 利用USB接口通过SDP连接PC
  - 简单的电源：9VDC输入
    - **ADP7118、ADP2442、ADP7182**
  - 测量同步
    - 触发输入/输出信号





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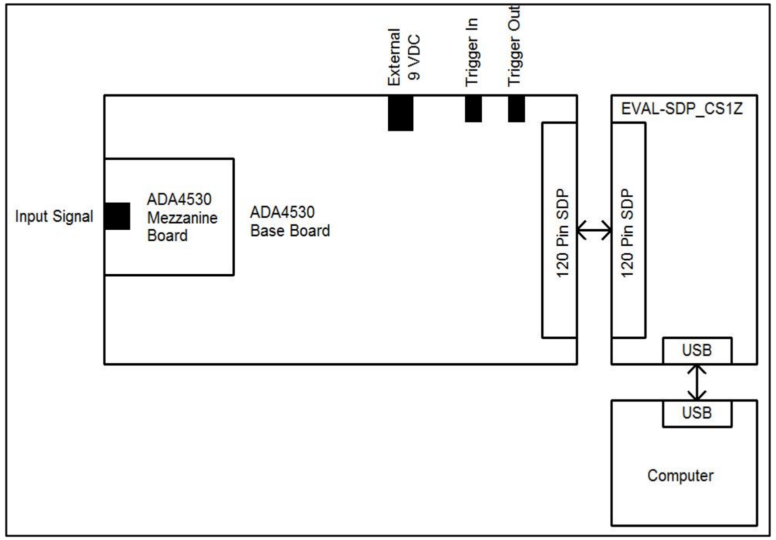
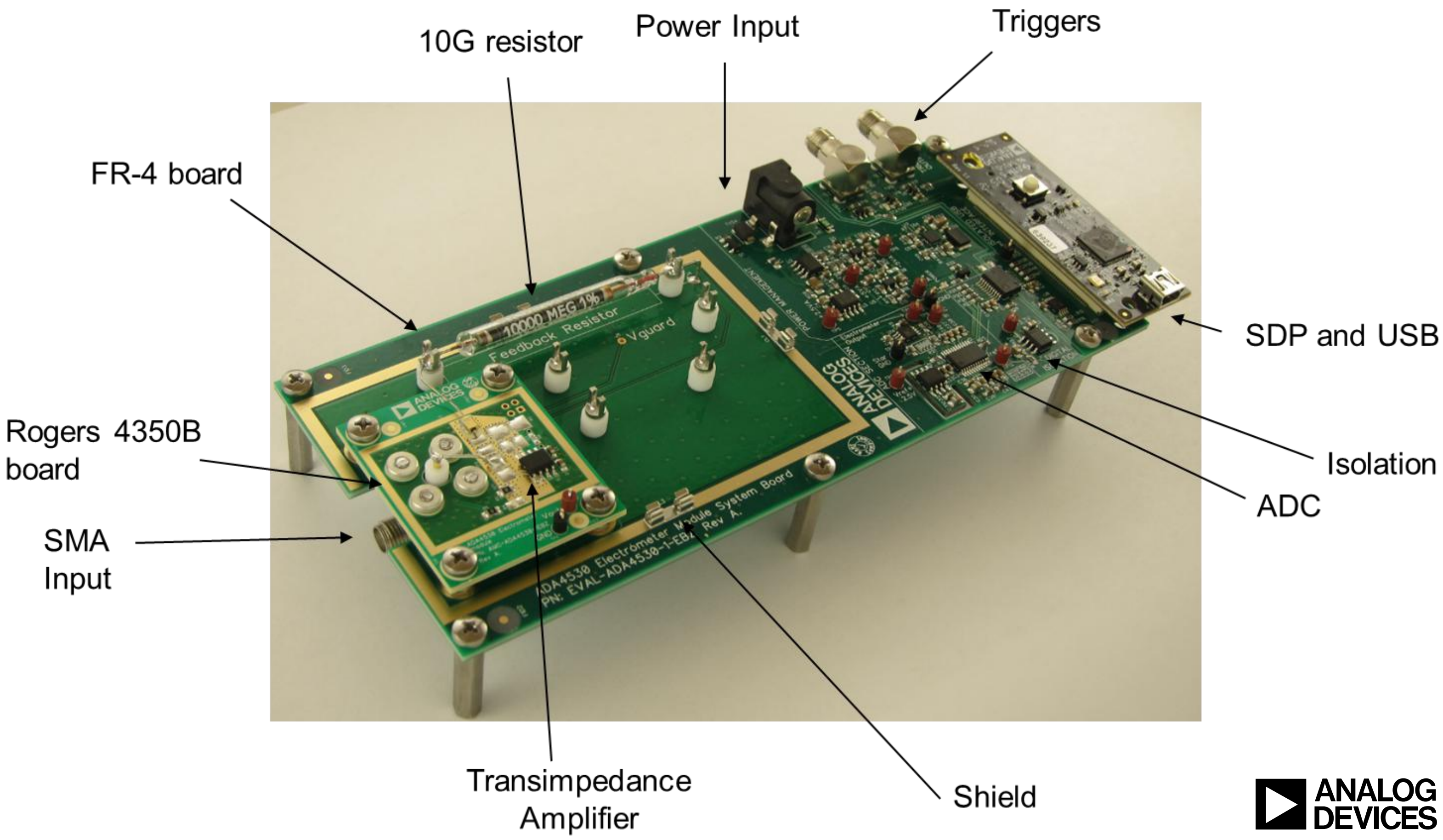
超高灵敏度飞安计模块

- 允许用户将传感器直接连到其应用环境中的电路板
- 针对实际应用而设计





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CN-0407：超高灵敏度飞安电流测量平台

ANALOG DEVICES

Circuit Note
CN-0407

Circuits from the Lab® Reference Designs

Circuits from the Lab® reference designs are engineered and tested for quick and easy system integration to help solve today's analog, mixed-signal, and RF design challenges. For more information and/or support, visit www.analog.com/CN0407.

Devices Connected/Referenced	
ADA4530-1	Femtoampere Input Bias Current Electrometer Amplifier
AD7172-2	Low Power, 24-Bit, 31.25 kSPS, Sigma-Delta ADC with True Rail-to-Rail Buffers
ADR4525	Ultralow Noise, High Accuracy, Voltage Reference
ADP2442	36 V, 1 A, Synchronous, Step-Down, DC-to-DC Regulator with External Clock Synchronization
ADG1419	2.1 Ω On Resistance, ±15 V/+12 V/±5 V, iCMOS SPDT Switch
ADP7118	20 V, 200 mA, Low Noise, CMOS LDO Linear Regulator
ADP7182	−28 V, −200 mA, Low Noise, Linear Regulator
ADuM3151	3.75 kV, 7-Channel, SPIsolator Digital Isolators for SPI

Ultrahigh Sensitivity Femtoampere Measurement Platform

EVALUATION AND DESIGN SUPPORT

Circuit Evaluation Boards
- CN-0407 Circuit Evaluation Board (EVAL-CN0407-SDPZ), Consists of Two Boards
  - Low Leakage Mezzanine Board (EVAL-CN0407-1-SDPZ)
  - Data Acquisition Board (EVAL-CN0407-2-SDPZ)
- System Demonstration Platform (EVAL-SDP-CS1Z)

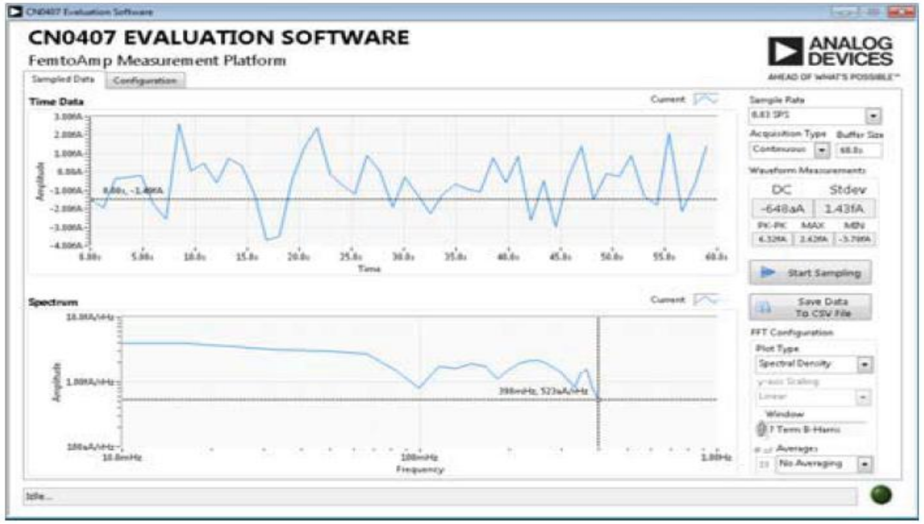
Design and Integration Files
- Schematics, Layout Files, Bill of Materials

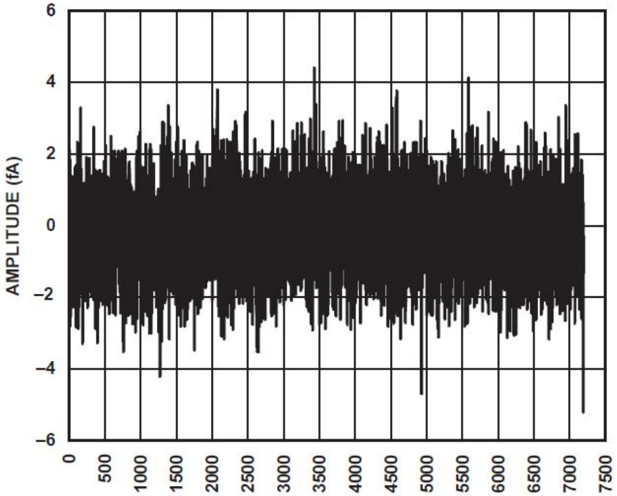
CIRCUIT FUNCTION AND BENEFITS

The system functional diagram in Figure 1 is a precision analog front end for measurement of current down to the femtoampere range. This industry-leading solution is ideal for chemical analyzers and laboratory grade instrument where an ultrahigh sensitivity analog front end is required for signal conditioning current output sensors such as photodiodes, photomultiplier tubes, and Faraday cups. Applications that can use this solution include mass spectrometry, chromatography, and coulometry.

The EVAL-CN0407-SDPZ provides a reference design for real-world application by partitioning the system into a low-leakage mezzanine board and a data acquisition board. The input signal conditioning is implemented with the ADA4530-1 on the mezzanine board. The ADA4530-1 is an electrometer-grade amplifier with ultralow input bias current of 20 fA maximum at 85°C. A guard buffer is integrated on the chip to isolate the input pins from leakage to the printed circuit board (PCB). The default amplifier configuration is in the transimpedance mode with a 10 GΩ glass resistor and a metal shield that prevents leakage current from entering any of the high impedance paths on the board. In addition, the mezzanine board includes unpopulated resistor and capacitor pads to allow prototyping with surface-mount feedback resistors as well as other input configurations.

The data acquisition board uses an AD7172-2 24-bit Σ-Δ analog-to-digital-converter (ADC) and is powered from a single 9 V dc supply. The on-board supply generates all necessary voltages required to power both boards. The board connects to a PC via the SDP-S board (EVAL-SDP-CS1Z) and uses digital isolation to prevent noise from the USB bus or ground loops from degrading low current measurements.





板噪声（输入开路，以0.83sps采样120分钟所得数据）

www.analog.com/CN0407

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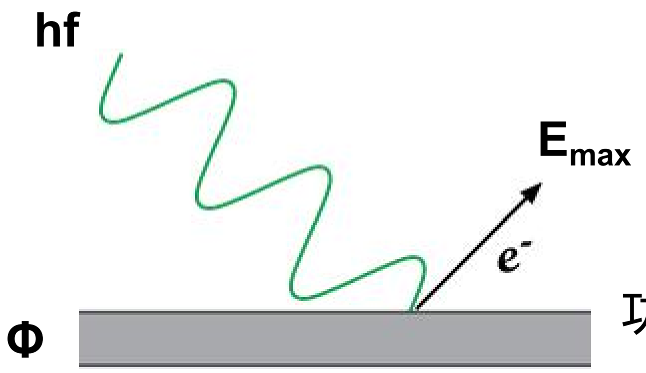
光电效应演示

低漏电流测量案例研究

光电效应

- 光照在光电发射材料上会打出电子



$$E_{max} = hf - \Phi$$

功函数Φ：从材料表面射出电子所需的最小能量

- 传感器：
  - 光电管（具有阳极和阴极的真空管）
  - 铯锑
  - 什么是光电管的功函数？

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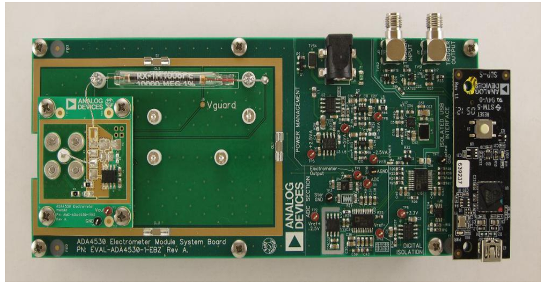
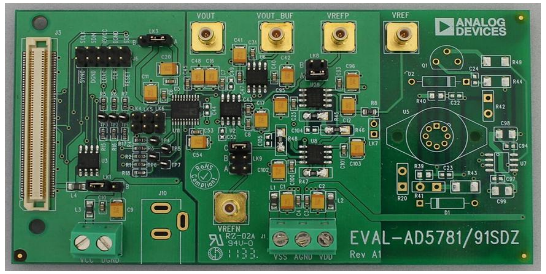
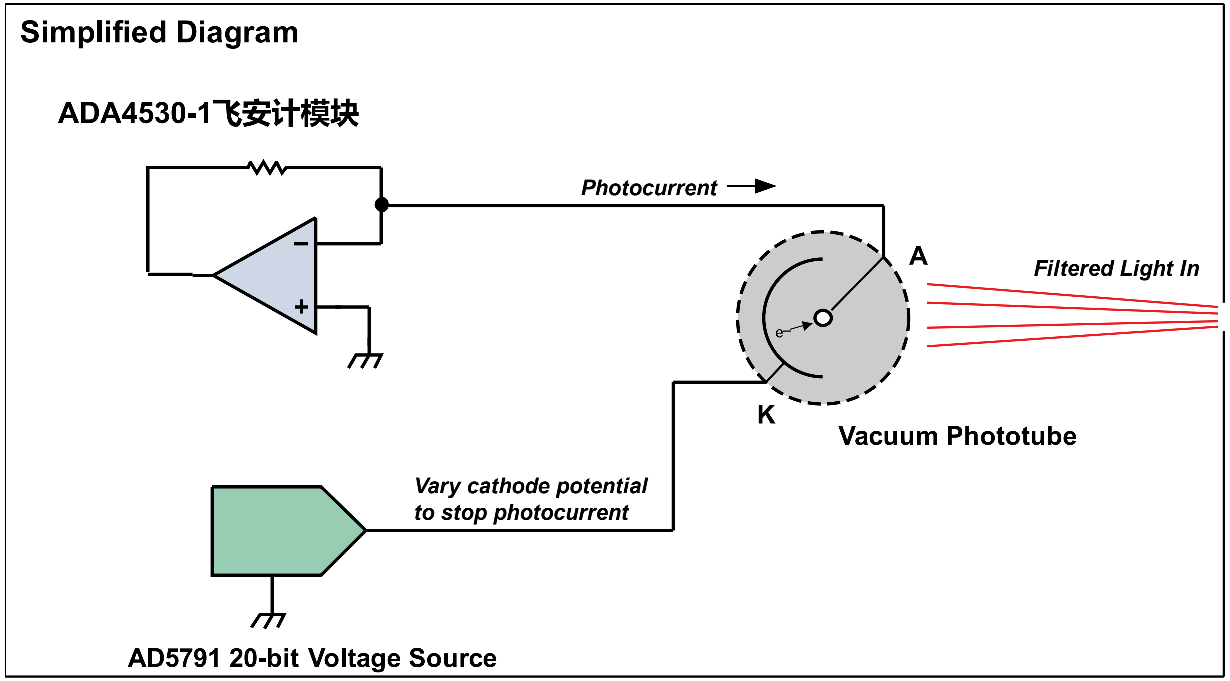
演示：利用ADA4530-1精确测量低至0 fA的电流

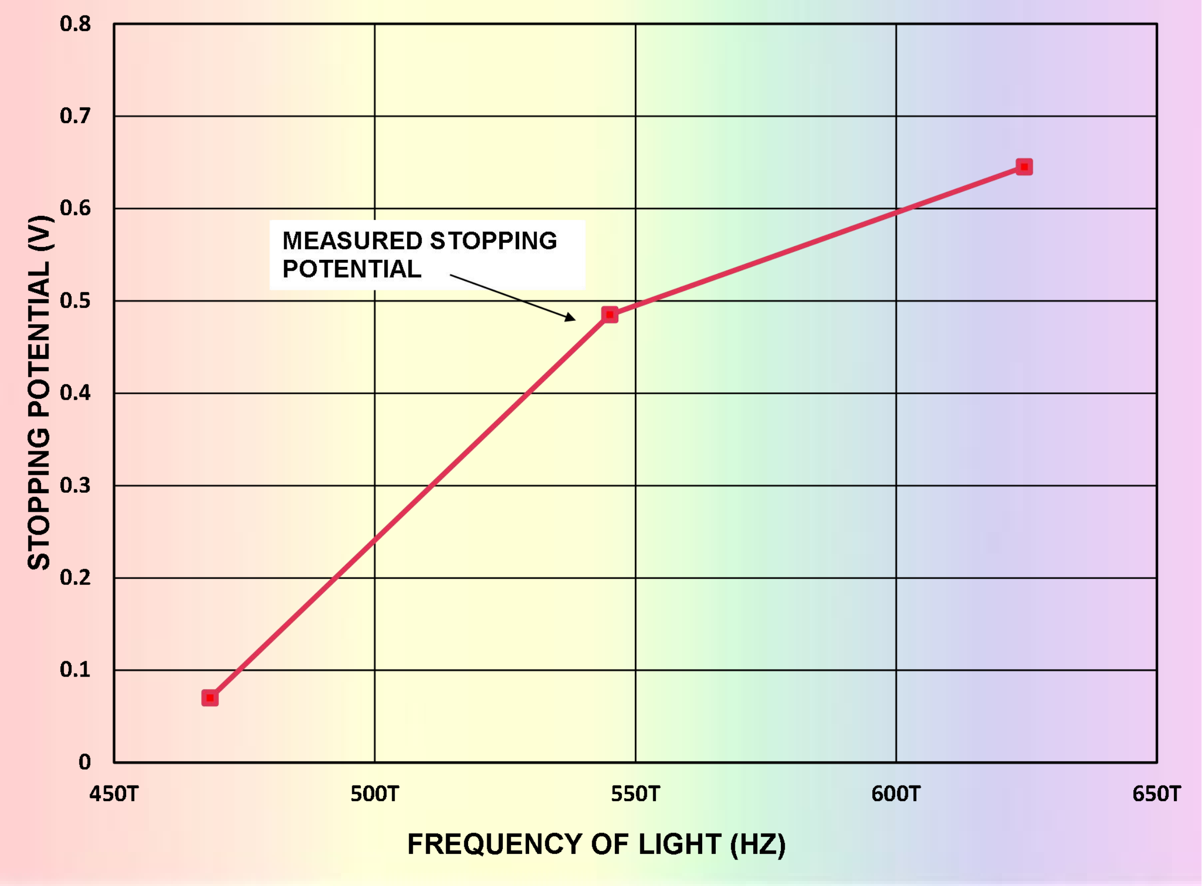






- 使用含铯锑材料的光电管
- 提供一个光源
- 测量光电流
- 施加一个与电子流相反的电压（遏止电位）以测量动能
- 计算功函数 $E_{max} = q \times V_{STOP} = hf - \Phi$

演示测量结果



- 遏止电位随预期光频率而变
- 功函数Φ实测值为1.86eV

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结论/收获

已学内容

- 为实现高灵敏度电流测量，必须使输出误差最小并使SNR最大。
  - 为使输出误差最小，需要使用低IB和低漂移的高精度放大器。
  - 为使SNR最大，要求精心选择增益器件。
- 设计低电流测量硬件需要考虑一些独特的问题。
  - 板漏电、污染、湿气、电介质吸收、线缆等可能会带来相当大的测量误差。
  - 运用最佳的保护、屏蔽、清洁/搬运方法，使用适当的板/焊接材料和布线来降低误差。
- ADI超高灵敏度飞安电流测量平台允许直接连接应用环境中的传感器。

有用链接

- ADA4530-1前端静电计(http://www.analog.com/media/en/technical-documentation/data-sheets/ADA4530-1.pdf)
- CN-0407：超高灵敏度飞安电流测量平台(www.analog.com/CN0407)
- 用户指南：UG-865 (http://www.analog.com/media/en/technical-documentation/user-guides/ADA4530-1R-EBZ_UG-865.pdf)
- 应用笔记：AN1373 (http://www.analog.com/media/en/technical-documentation/application-notes/AN-1373.pdf)

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