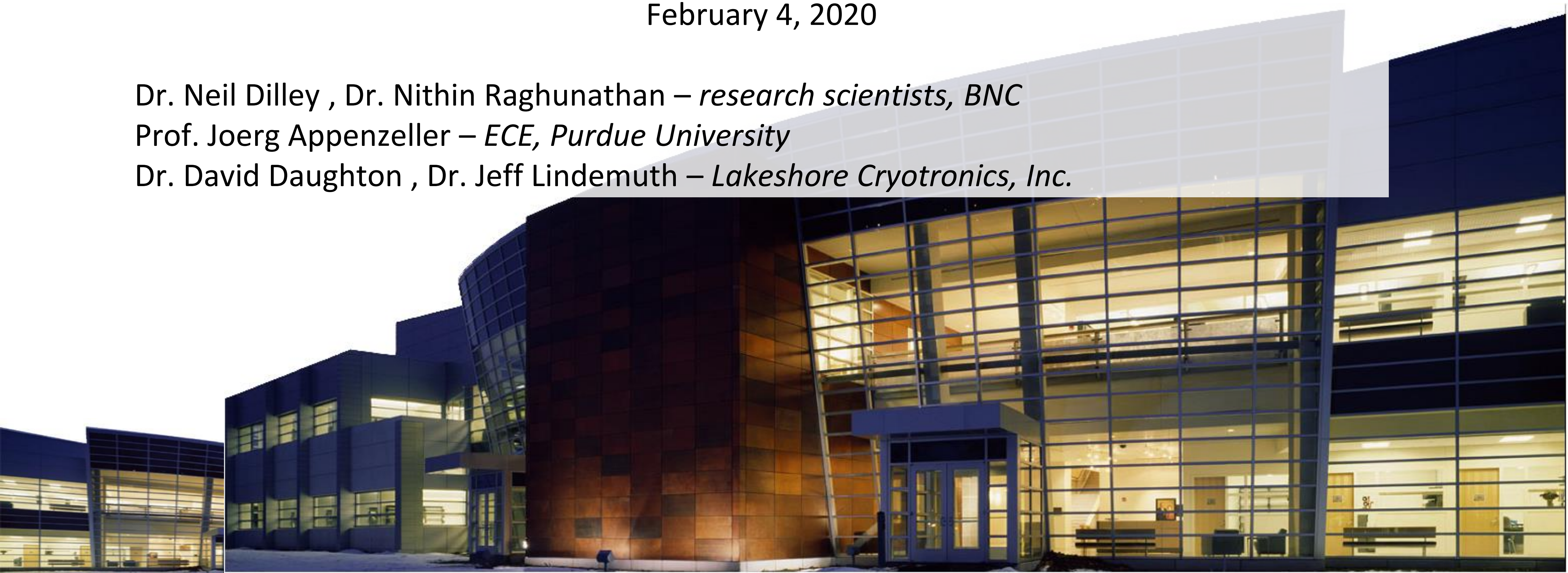
Birck Tutorial: a practical guide to electrical characterization of materials

Birck Nanotechnology Center (BNC), Purdue University
February 4, 2020

Dr. Neil Dilley , Dr. Nithin Raghunathan – *research scientists, BNC*
Prof. Joerg Appenzeller – *ECE, Purdue University*
Dr. David Daughton , Dr. Jeff Lindemuth – *Lakeshore Cryotronics, Inc.*



program for tutorial

Welcome from Prof. Ali Shakouri *(Director, BNC)*	*9:00 – 9:15 am*
Prof. Joerg Appenzeller *(ECE)* nanodevice characterization	*9:15 – 10:00 am*
Dr. David Daughton *(LakeShore Cryotronics, Inc.)* LakeShore probe stations: cryogenics, magnetic fields low current measurements	*10:00 – 10:45 am*
BREAK	*10:45 – 11:00 am*
Dr. Nithin Raghunathan *(BNC)* Overview of Birck's fleet of probe stations Using Kelvin probes wire bonding practical guidance dicing saws	*11:00 – 11:45 am*
LUNCH (provided), TOURS	*11:45 am – 1:00 pm*
Dr. Jeff Lindemuth *(Lakeshore Cryotronics, Inc.)* new FastHall measurement technique	*1:00 – 1:30 pm*
Dr. Neil Dilley *(BNC)* Testing electrical contacts Choosing measurement electronics	*1:30 – 2:15 pm*
BREAK	*2:15 – 2:30 pm*
PANEL DISCUSSION : Q&A, advice...	*2:30 – 3:00 pm…*

food is courtesy of:

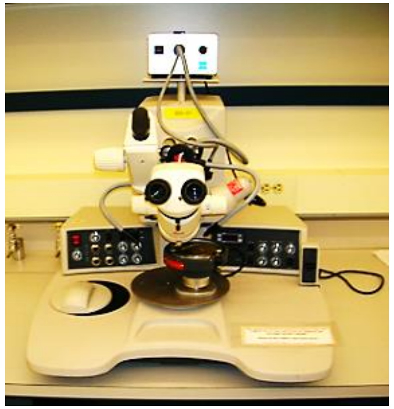
Lake Shore CRYOTRONICS
ADVANCING SCIENCE

and

BNC Spintronics Lab

why this tutorial?

- **Mentorship**
- **Community**
- *practical* guidance, beyond textbook
- open to all levels of users



research scientists at BNC

Rosa Diaz Rivas – Electron Microscopy Staff Scientist
Expert in: SEM, TEM, E-TEM, E-STEM, HREELS
Ph.D., MSE, Arizona State U. (2010); Brookhaven; Okinawa
rdiazri@purdue.edu ; Ph. x61075 ; Ofc. BRK 1272

Neil Dilley – Research Scientist
Expert in: magnetic measurements, cryogenics, outreach
Ph.D., Physics, UC San Diego (1999); Quantum Design, Inc.
ndilley@purdue.edu ; Ph. x66080 ; Ofc. BRK 1010

Nick Glassmaker – Research Scientist
Expert in: roll to roll, polymer processing, mechanical testing
Ph.D., ME, Cornell (2004); DuPont
nglassma@purdue.edu ; Ph. x44312 ; Ofc. BRK 1010

Alexei Lagoutchev – Senior Research Scientist
Expert in: lasers and almost anything optical
PhD, Physics/Math (1993), Inst. Gen. Physics, Russia; Taiwan
lagutch@purdue.edu, Ph. x6539; Ofc. BRK 1276

Ye Mi – Research Scientist
Expert in: R2R characterization, tomography, two-phase flow
Ph.D., Nuclear Eng., Purdue (1998); En'Urga, Inc.
yemi@purdue.edu; Ph. x68253; Ofc. BRK 1019

Charilaos (Harris) Mousoulis -- Senior Research Scientist
Expert in: BioMEMS, integrated sensor design, IoT systems
Ph.D., ECE, Purdue (2012);
cmousoul@purdue.edu ; Ph. x49938; Ofc. BRK 1268

Nithin Raghunathan – Research Scientist
Expert in: MEMS, wireless devices, electrical characterization
Ph.D., ECE, Purdue (2014);
nithin@purdue.edu; Ph. x67326; Ofc. BRK 2038

Dmitry Zemlyanov - Senior Research Scientist
Expert in: Surface Science
Ph.D., Physics/Math, Novosibirsk State Univ. (1995);
dzemlian@purdue.edu ; Ph. x62457; Ofc. BRK 1274

We are here to help, please use us!

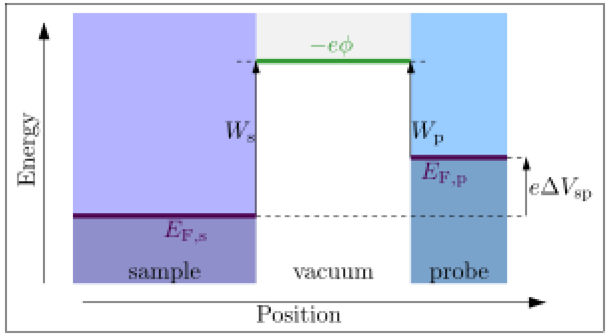
before doing anything, consider...

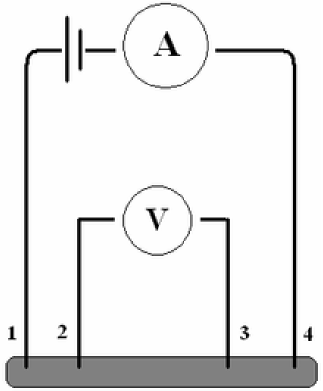
- ☐ What am I trying to learn?
- ☐ What is anticipated signal level?
- ☐ Which electronics can measure this signal?
- ☐ Which is the best instrument? B-field, temperature, cable guarding...
- ☐ *...then you can start planning you sample design!*

Early discussion with PI, research scientist, or visit to library is best investment!

Kelvin probing

Kelvin probing: non-contact, measures diff. in work fn. Between materials, generate charge Q = C*deltaPsi
In Probe stations, “Kelvin probes” refer to separating the force and sense probes (= 4-probe measurement)
Wikipedia, “4-terminal sensing”: “Four-terminal sensing is also known as Kelvin sensing, after William Thomson, Lord Kelvin, who invented the Kelvin bridge in 1861 to measure very low resistances using four-terminal sensing. Each two-wire connection can be called a Kelvin connection. A pair of contacts that is designed to connect a force-and-sense pair to a single terminal or lead simultaneously is called a Kelvin contact. A clip, often a crocodile clip, that connects a force-and-sense pair (typically one to each jaw) is called a Kelvin clip.”

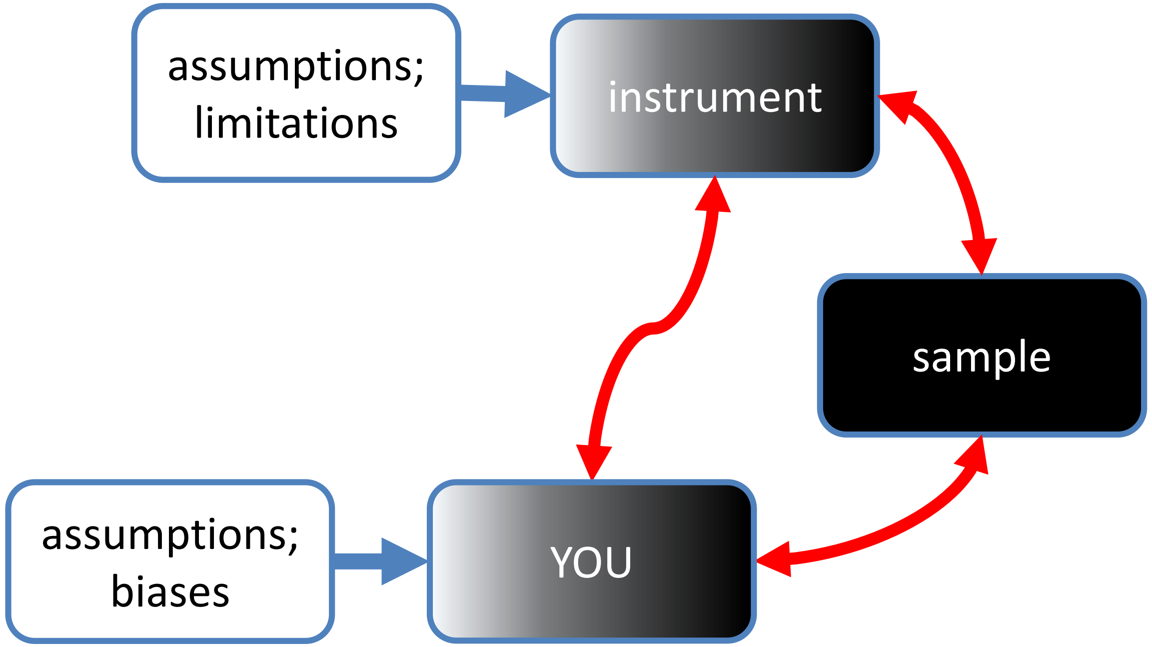




the “black boxes” effect: they are everywhere!

Marconi and his “black box”

Semiconductor parameter analyzer



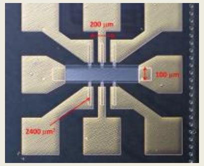
assumptions; limitations

instrument

sample

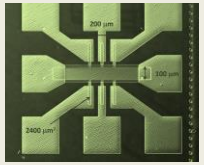
assumptions; biases

YOU



nist.gov

your sample



control sample

reference sample

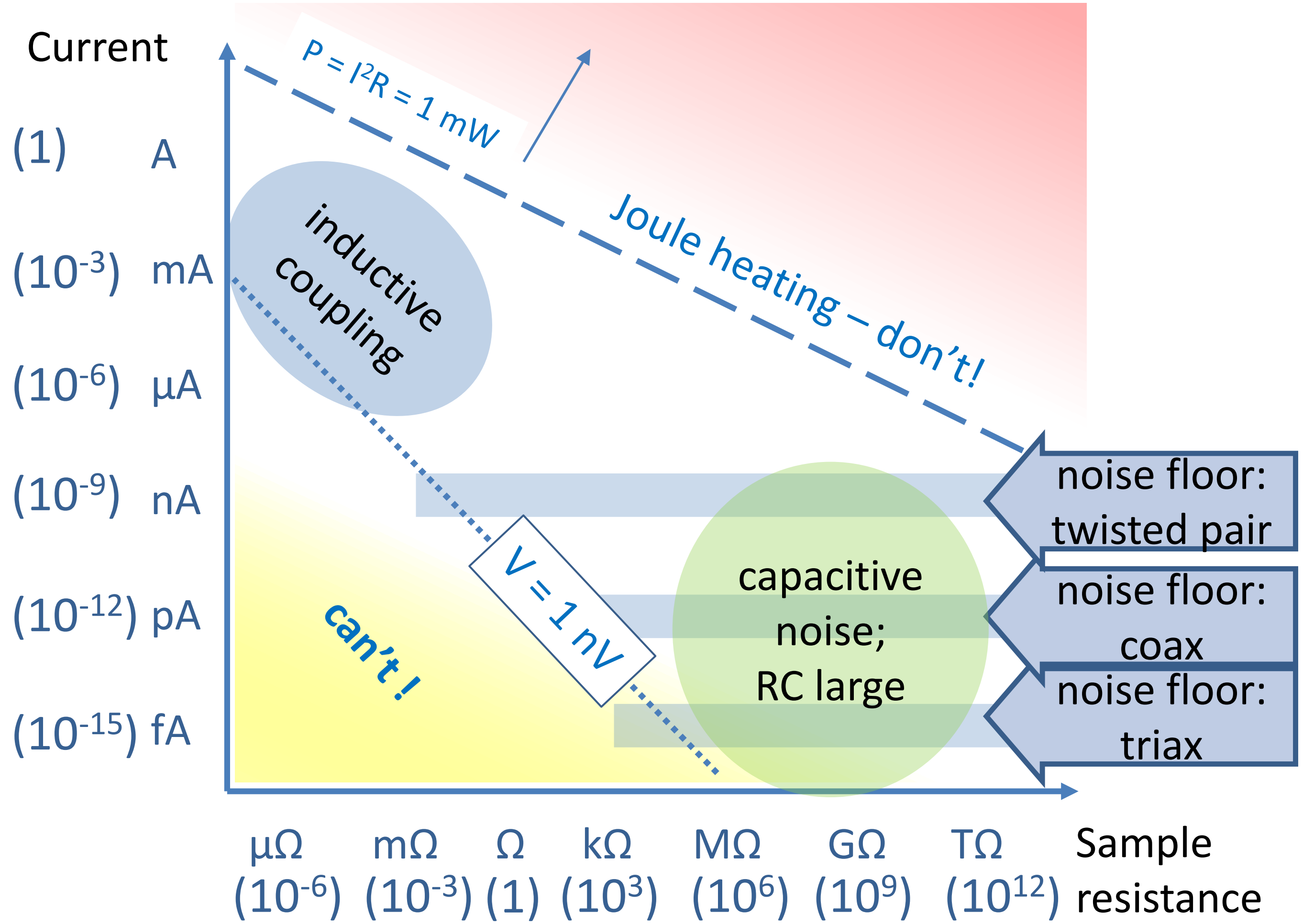
Do you know what you’re measuring? It’s easy to be fooled!

playground for electrical characterization

best *inductive* screening

LakeShore App Note

best *capacitive* screening



Current

(1) A

(10^{-3}) mA

(10^{-6}) µA

(10^{-9}) nA

(10^{-12}) pA

(10^{-15}) fA

$P = I^2R = 1$ mW

Joule heating – don't!

inductive coupling

can't !

V = 1 nV

capacitive noise;
RC large

noise floor: twisted pair

noise floor: coax

noise floor: triax

µΩ (10^{-6}) mΩ (10^{-3}) Ω (1) kΩ (10^{3}) MΩ (10^{6}) GΩ (10^{9}) TΩ (10^{12})

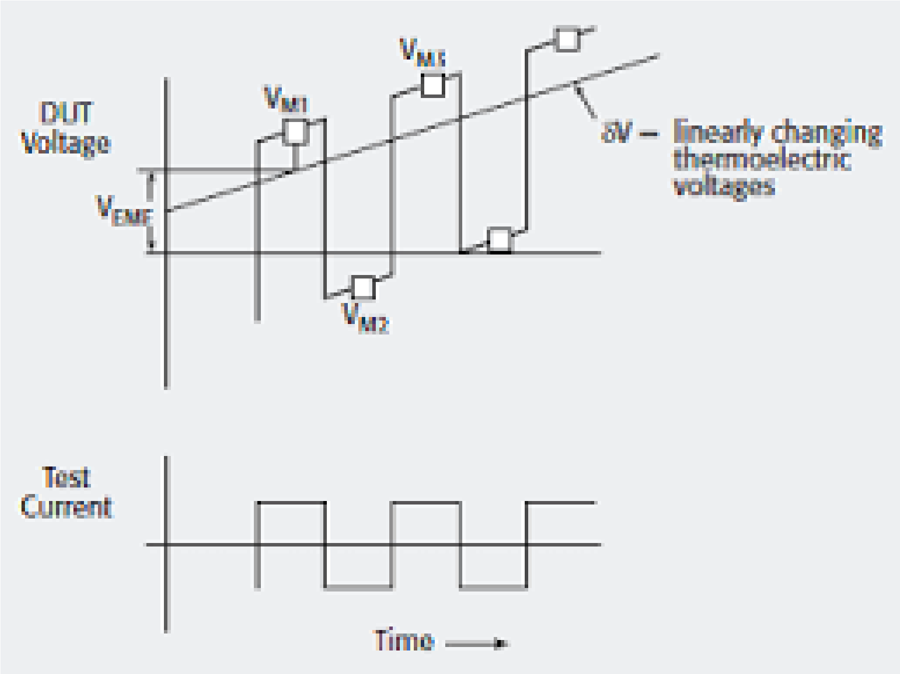
Sample resistance

Choose correct cabling to minimize noise

modulate the drive to cancel offsets

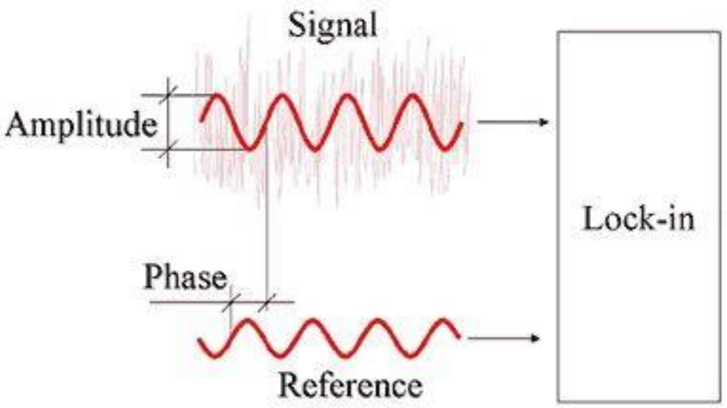
Gets rid of:

- thermoelectric EMFs
- amplifier drift
- anything *slow* or independent of *sign* of the drive
- still looking at DC signals
- for best sensitivity, use a “lock-in amplifier”



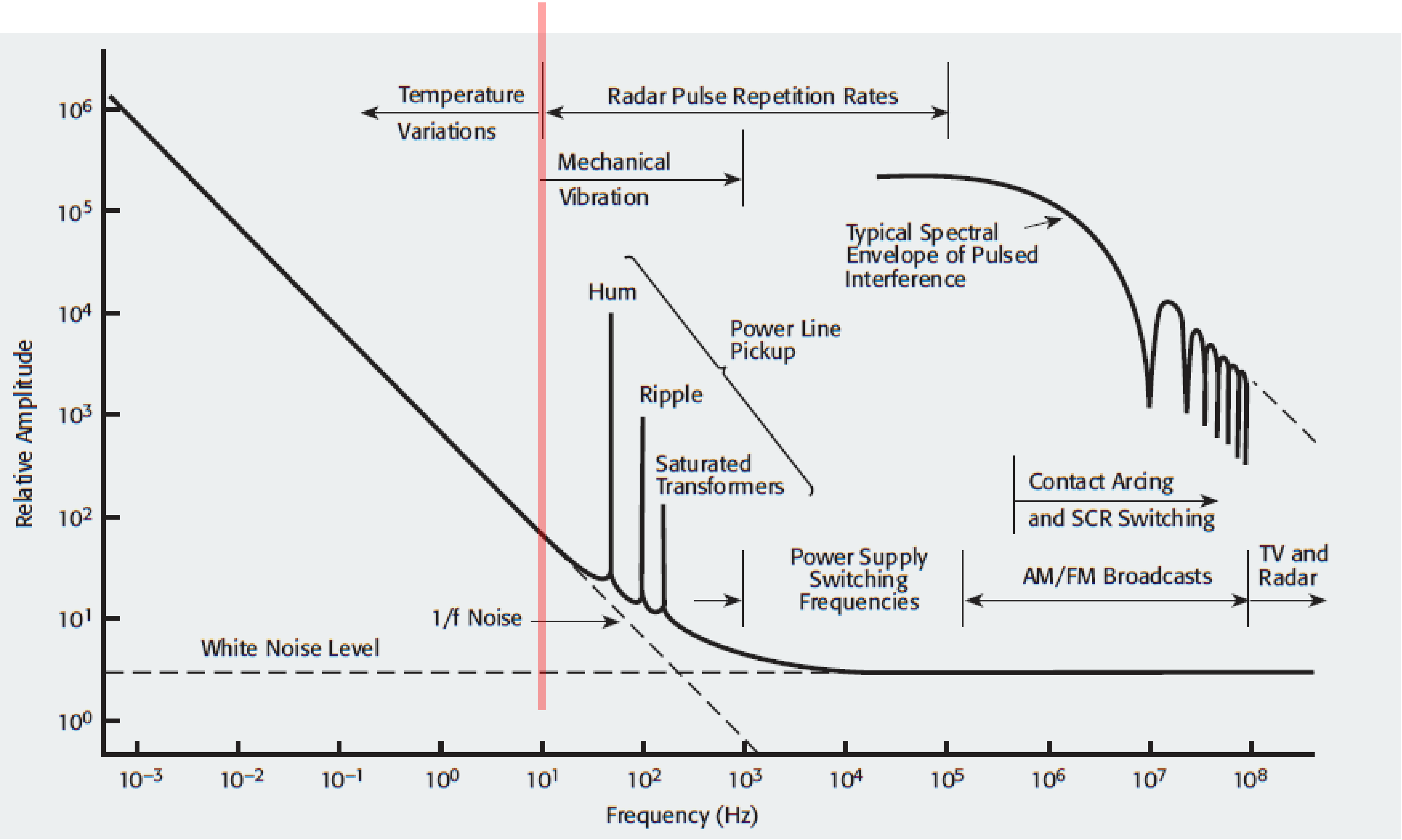
modulation is a “must” for low resistance measurements

why use a lock-in? “narrow banding”



example: f = 10 Hz

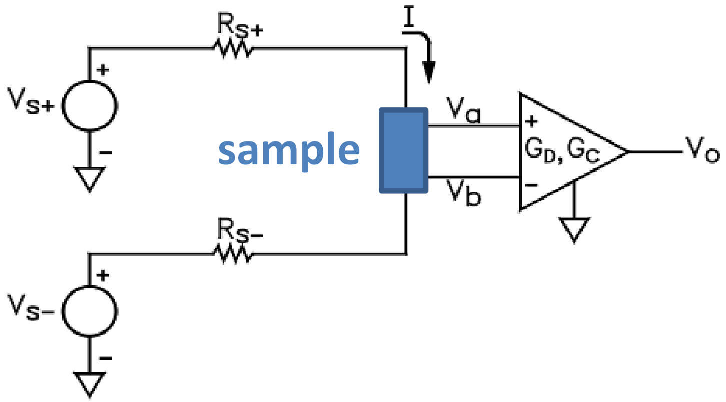
DC measurements catch wide range of frequencies, but lock-in only sees red band



Low voltage measurements need help – lock-in amplifiers to the rescue!

"symmetric" drive is best

Quantum Design ETO



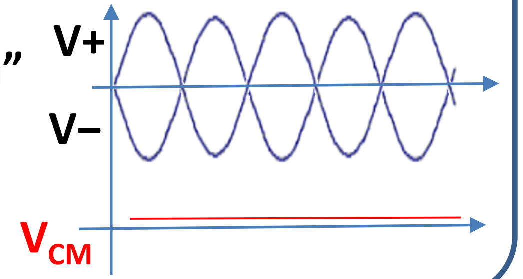
$$\frac{G_D}{G_C} \equiv \mathrm{CMRR}$$

Ideal output: $V_{ideal} = (V_a - V_b)\, G_D$

True output: $V_o = (V_a - V_b)\, G_D + \left(\frac{V_a + V_b}{2}\right) G_C$

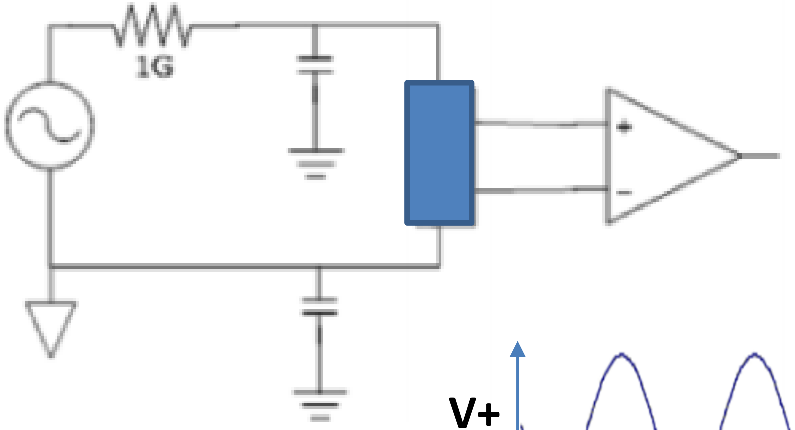
"common mode leakthrough"

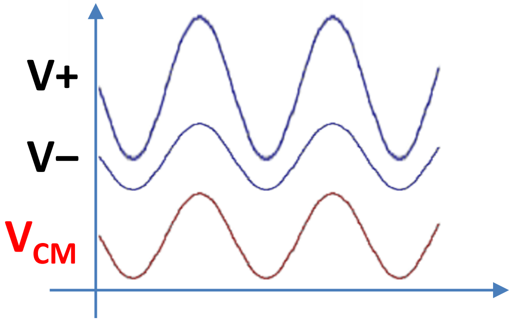
$V_{CM} = (Va + Vb)/2 \approx 0$



VS.

Most custom setups (Keithley...)





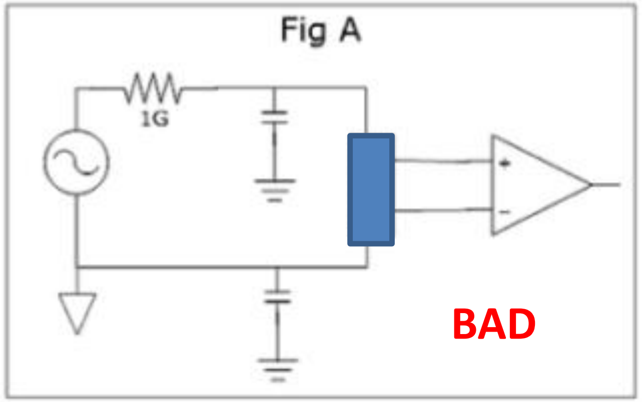
"common mode leakthrough"

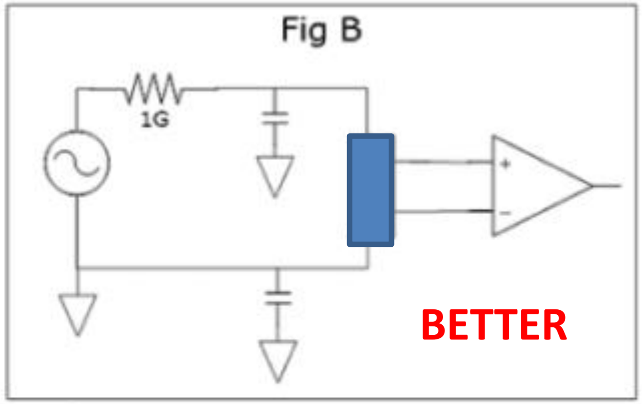
$V_{CM} = (Va + Vb)/2 \approx I*(Rsample/2 + Rcontact) \neq 0$

Common mode signals are offsets that can't be subtracted, important when R_{sample} small

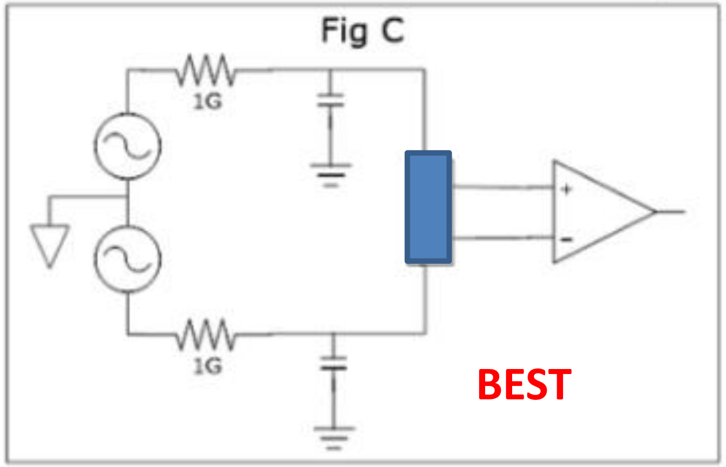
symmetric drive also improves noise

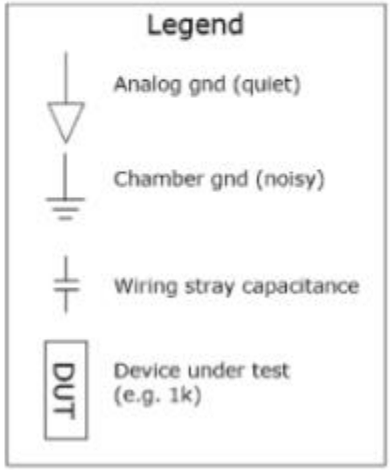
Most custom setups





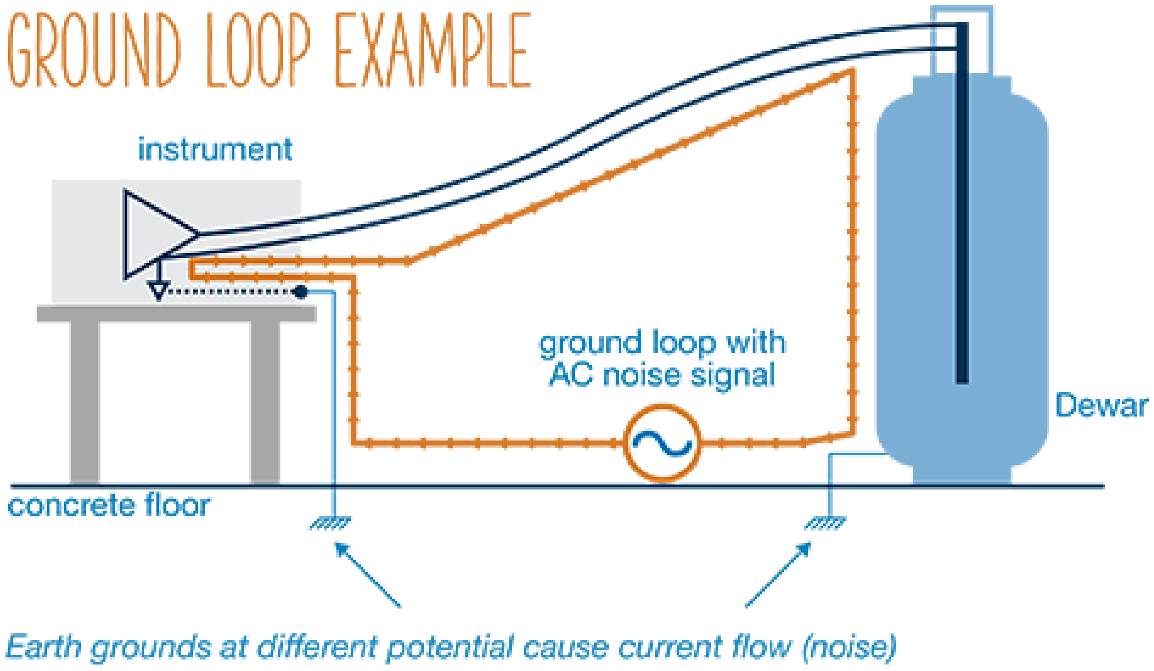
Quantum Design ETO





balanced source impedance cancels the noise

avoiding ground loops



Make a table (this one from BNC Wiki):

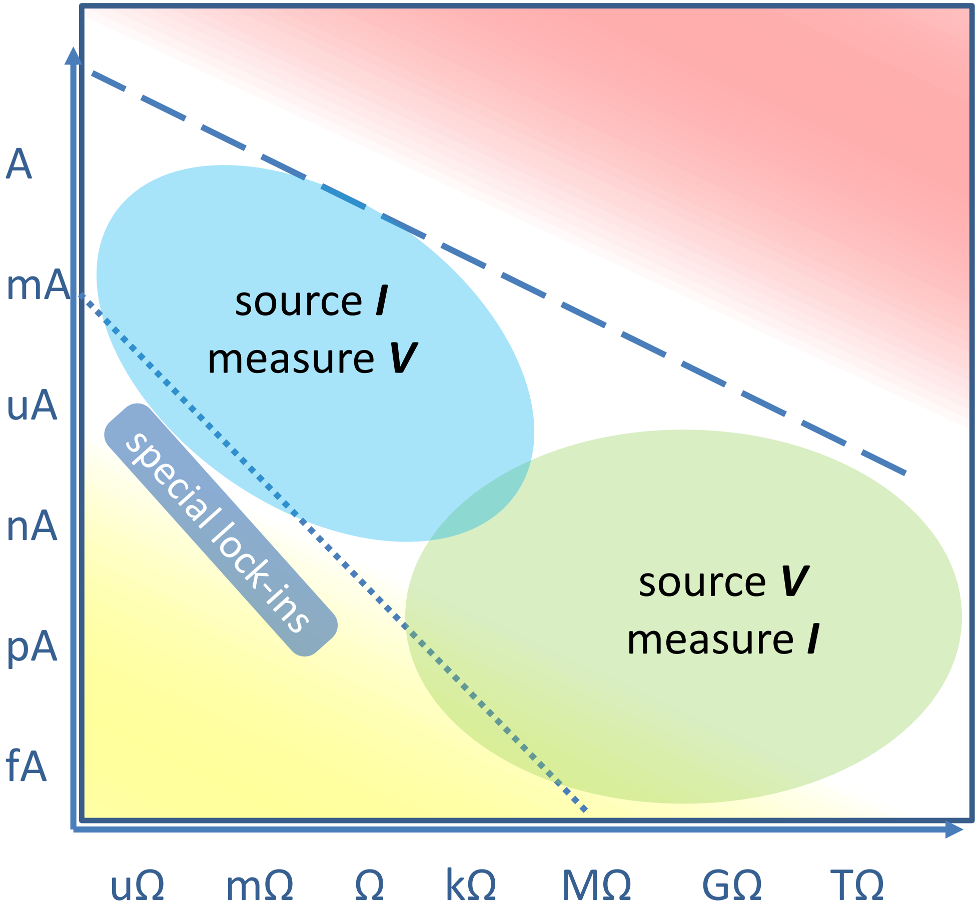
BNC switchbox					External electronics (SMUs)	
Sample contact	**DIP**	**Ctr (F/G)**	**Shld (F/G)**	**Gnd Ref.**	**Shld Fn.**	**Make&Model ; cable connections ; comments**
GND wire for box (green) = G						Looped back to switchbox body
I+	1	F	G	Y	I-	K6221 triax-BNC;
I-	2	F	G		X	(connects to 6221 through cable to I+)
V+	15	F	G		F	SR830 A
V-	16	F	G		F	SR830 B
Measurement: Hall bar using “A-B” mode on SR830; **K6221** lock-in trigger: from 6221 TRIGGER LINK pins 3 & 8 (8=digital common) to BNC to SR830 REF IN. - Set up trigger: config/wave/phasemkr. Phase marker = enabled, phase = 180 deg, pin=3. - Using Signal Ground as Gnd Ref: output low=earth ground (Sec. 2-6 of 6221 manual) - set Triax/Inner Shield = Guard (this won’t be used when converting triax/BNC) SR830: float the shields (“Ground” button) in Signal Input section on front panel.						
LEGEND: **F** = float ; **G** = ground ; **X** = not connected ; **ban** = banana plug						

Choose the quietest ground reference as the ONLY ground

selecting electronics

V sensitivity

- Quantum Design ETO
- Keithley 6221 AC current + SR830 lock-in
- Keithley 6221 DC current (delta mode) + Keithley 2182A nV-meter
- Keithley 2400



- Agilent 4156C
- Keithley 2636B
- Keithley 6487 pA-meter and V source
- Quantum Design ETO
- Keithley 2400

I sensitivity

Now you can choose electronics, probe station and start designing sample

sample geometry: 4-wire measurements

$\rho = R(w \cdot t)/\ell$

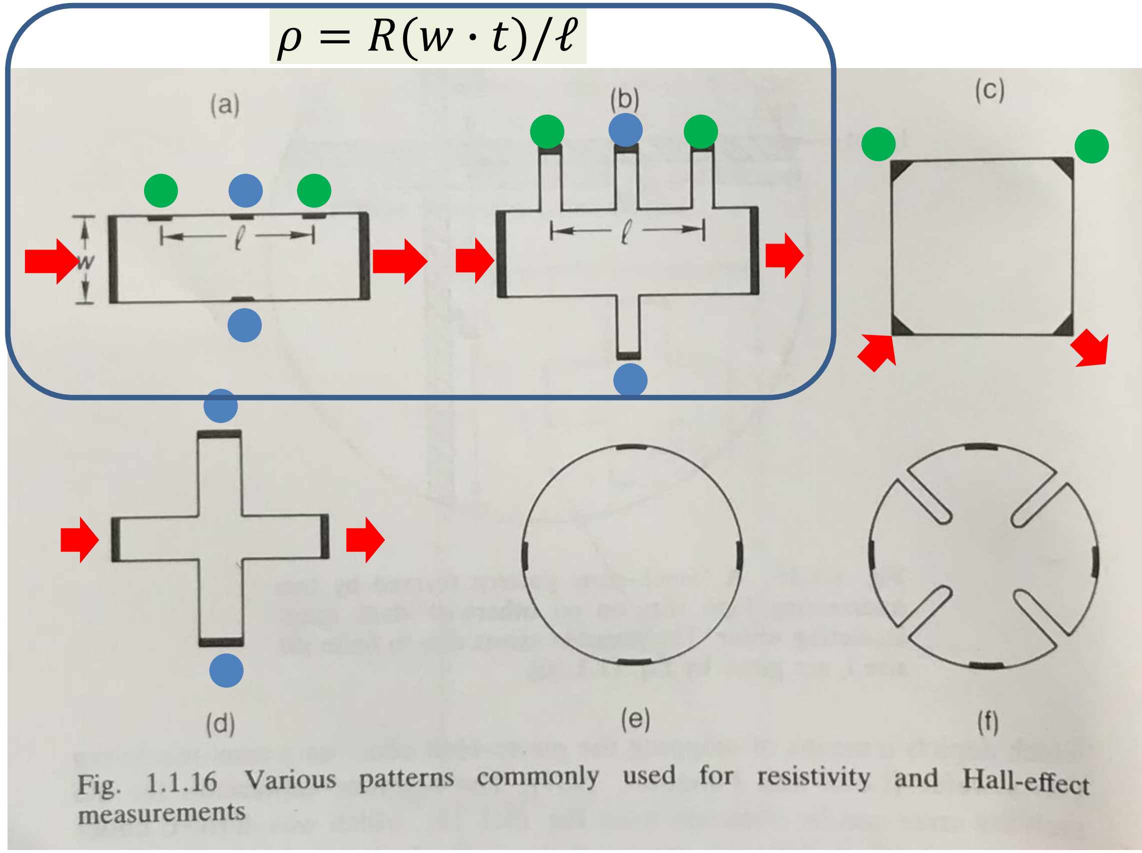


Fig. 1.1.16 Various patterns commonly used for resistivity and Hall-effect measurements

D. Look

Resistivity Voltage pads

Hall effect Voltage pads

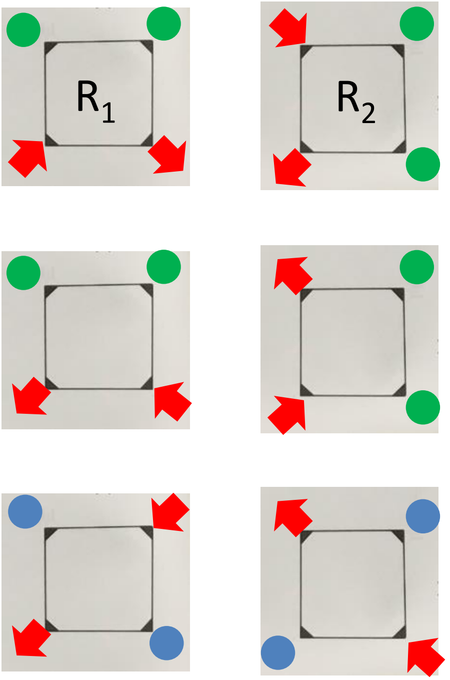
Current pads

sample thickness ***t***

van der Pauw method

$$\rho = \frac{\pi t}{ln2}\left[\frac{R_1 + R_2}{2}\right] f$$

$f \approx 1$
(square sample)



resistance

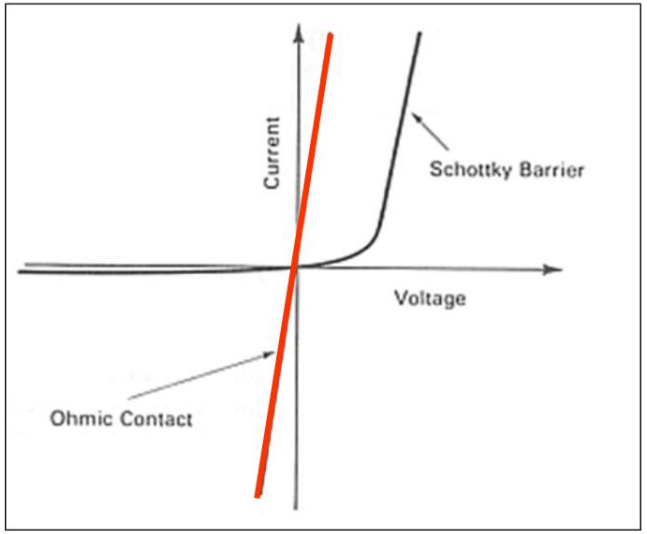
reversal

Hall
(+ reversal)

4-wire (“Kelvin”) method removes many (but not all!) contact issues

contacting your sample

> “what should be the simplest part of a Hall-effect measurement, namely, putting on the contacts, is often the most troublesome.”
>
> - D.C. Look, speaking about GaAs



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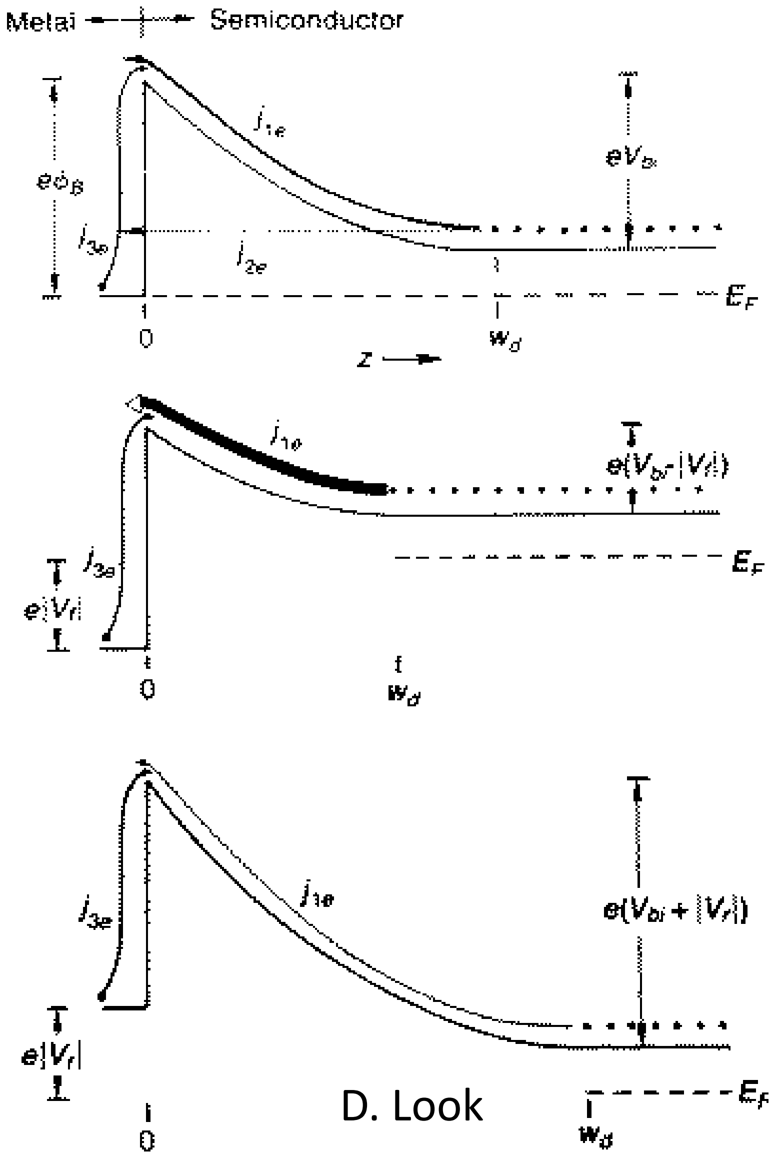

D. Look

<u>Example:</u>

- Plasma clean sample surface
- evaporate Ti-Au contacts
- Au wire bond OR probe station

<u>Notes:</u>

- Ohmic contacts
- I-V curve is proof!
- check again at low T

<u>Some methods to try:</u>

1. wire bond
2. (ultrasonic) solder
3. pressed indium
4. silver epoxy
5. press contacts
6. silver paint

Sample contacts are your research project, not a distraction

references

- **The Hall Effect and Related Phenomena**, E. H. Putley
- **Electrical Characterization of GaAs materials and Devices**, David C. Look
- **Low Level Measurements Handbook**, 7th Edition, Keithley Inc.,
- www.qdusa.com Application Notes :
  - 1584-201 (common mode leakthrough)
  - 1584-202 (inductive cross-talk)
  - 1070-212 (probe for ESD-sensitive devices)
- **The Art of Electronics**, Horowitz and Hill
- BNC Wiki page for Electrical and Magnetic Properties: https://wiki.itap.purdue.edu/x/NgRVB

Other Resources

- M. Lundstrom: **ECE 656 class notes; Fundamentals of Carrier Transport**; https://nanohub.org/groups/ece656_f17
- simulations on nanoHUB ...
  - e.g., **Optimized Workflow for Electronic and Thermoelectric Properties** https://nanohub.org/resources/owetp/about
- M. Alam: **ECE 695A Reliability Physics of Nanotransistors**, https://nanohub.org/resources/16560
- M. Alam: **ECE 695E: An Introduction to Data Analysis, Design of Experiment, and Machine Learning** https://nanohub.org/resources/28817
- **Electric Contacts: Theory and Application**, Ragnar Holm
- **Electrical Contacts**, Braunovic et al.