Quantum Design electrical transport
user training seminar

part 1: theory of operation

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Neil Dilley, Ph.D.
Quantum Design, Inc.

outline of seminar

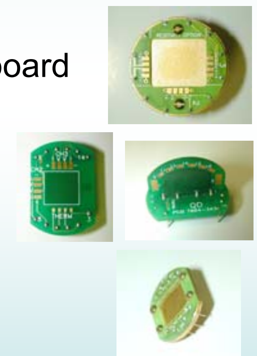
- Resistivity option
- AC Transport option
- Electrical Transport Option

- transport further reading

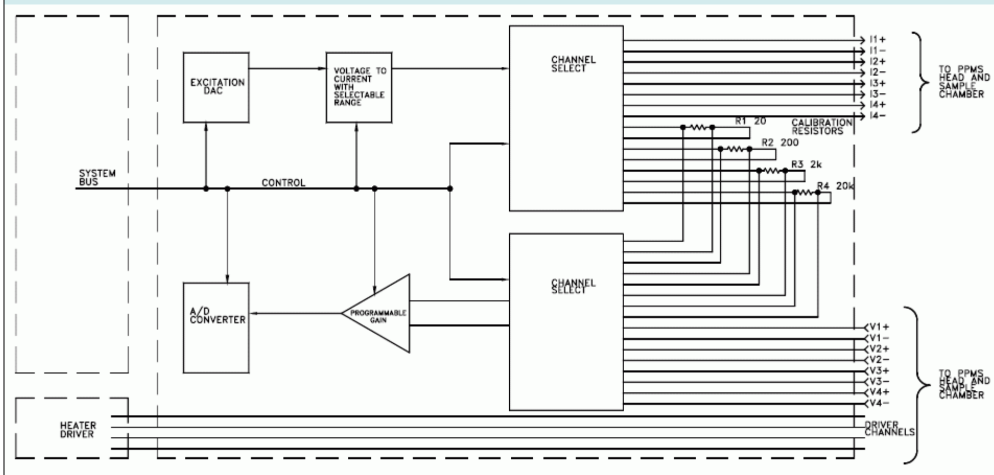
- subtopics for each option:
  - hardware
  - measurement modes
  - specifications

Resistivity option: hardware

- uses resistance bridge developed for reading thermometers of system
  - inside Model 6000 controller
  - system uses identical System Bridge board
- available in these mount styles:
  - puck (top)
  - rotator (middle)
  - Helium-3 insert (bottom)

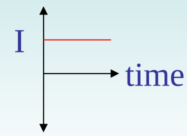


Resistivity option: bridge block diagram

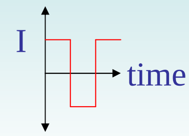


- one source/meter multiplexes to 4 channels
  - channel leads are open circuit when not being measured
- on-board (Vishay) standard resistors to recalibrate current source
- Note 2 heater drivers (1 amp or 20 watts) are available

Resistivity option: theory of operation



d.c.



a.c.

- d.c. current source: 5 nA to 5mA
- “a.c.” mode chops +/- current to remove thermal voltage offsets
- bridge clock cycles at 15 Hz (16.7 Hz) in 60 Hz (50 Hz) regions
  - cycle 1: apply +current to channel 1 and digitize voltage
  - cycle 2:
    - IF Ch.1 using a.c. mode, apply –current to Ch.1 and digitize voltage
    - ELSE go to next ON channel and repeat cycles 1-2
- acquisition speed depends on # of active channels and a.c/d.c mode
  - standard mode: recalibrates current source every 60 sec. or when excitation settings change (uses Vishay resistors)
  - fast mode: does not recalibrate current source

Resistivity option: measurement modes

- Resistance R
- “Scan Excitation”: R vs. I (like I-V curve)
  - measures voltage at each d.c. current
  - improved on Multivu version 1.5.0 (on QD website)
  - good probe of V+/- contacts: are they ohmic? R.vs.I should be flat!
- voltage mode
  - current source turned off, reported value now mV
  - see PPMS Resistivity app. note 1076-303

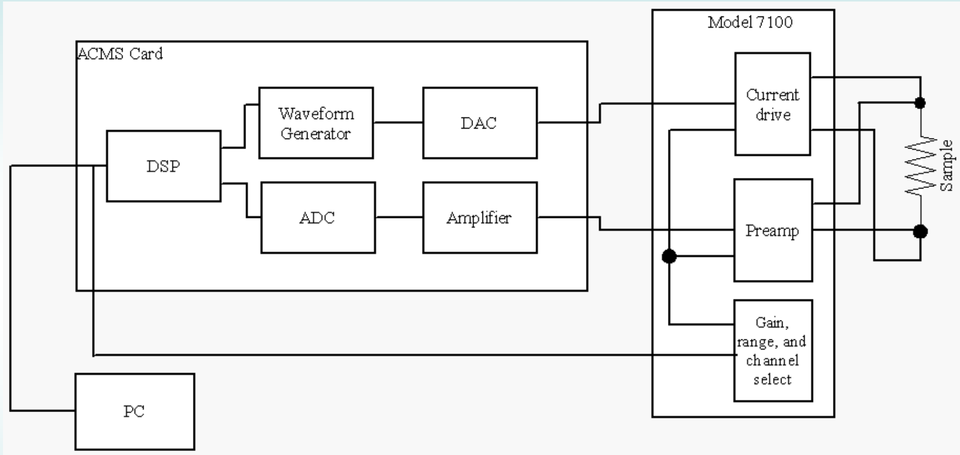
Resistivity option specifications

- d.c. current source
  - 5 nA to 5 mA excitation
  - d.c. and a.c. modes
- voltmeter
  - up to 4 readings/sec
  - voltmeter rms noise = 20 nV x (averaging time)^{½}
    - written as “20 nV/rt-Hz”
  - voltmeter max input = 95 mV
- one source/meter multiplexes to 4 channels
  - channel leads are open circuit when not being measured
- good for R **~ 1 Ohm up to 1 MOhm**

AC Transport (ACT) option hardware

- ACMS card is engine
  - generates excitation waveform
  - digitizes voltage signal from sample
- Model 7100 provides
  - amplification of current signal up to 2 amps
  - preamplifier of sample signal
  - potentiometers for 5-wire Hall adjustment
  - monitor BNCs for current and voltage

ACT block diagram



- one source/meter multiplexes to 2 channels
  - channel leads are open circuit when not being measured
- waveforms: sine, pulse, triangle, sawtooth
- no practical user-to-DSP (i.e., custom) communication possible

ACT theory of operation: a.c. mode

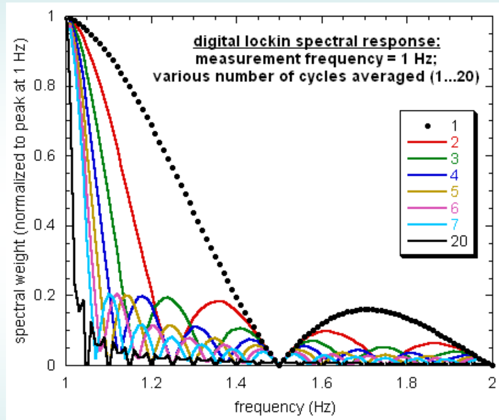
- digital lock-in at frequency ω
  - multiple cycles are summed to make a 1-cycle dataset *V(t)*
    - equivalent to keeping in original V(t) train, just a DSP convenience
  - DSP computes V_ω = amplitude of voltage signal at ω
  - boxcar averaging used (vs. running average in typical analog lock-in)
  - harmonic info is almost free, gives info on distortion of V(time) signal

$$V_\omega = \int_0^{2\pi/\omega} \sin(\omega t)\cdot V(t)dt$$

$$V_{N\omega} = \int_0^{2\pi/\omega} \sin(N\omega t)\cdot V(t)dt$$

ACT theory of operation: a.c. mode

- “narrow-banding” through more averaging
- note “lobes” in response due to finite averaging time
- always node at 1.5x(freq)
- same lockin method in:
  - VSM
  - ACMS



ACT theory of operation: I-V, c.c.

- current source outputs triangle wave
- d.c. voltage reading taken at each current step
  - waits "settling time" before starting V reading
  - averages for N x (line cycles)

ACT measurement modes

- resistivity ρ = R * (Area/Length)
  - sinewave excitation I, digital lockin of voltage V
    - R = V/I
  - need user's estimate of Area/Length
- Hall coefficient $R_H = \rho / B$
  - same measurement as ρ
  - uses reported magnetic field B to compute R_H
  - 5-wire method available; reduces voltage lead imbalance
- I-V curve
  - **d.c.** voltage read at each current step
- critical current
  - an I-V measurement where current ramp stops once a threshold voltage reached (avoids heating/damage in SC samples)
  - only reports current value at the threshold voltage

ACT specifications

- current source range: 10 μA to **2 A**
- voltmeter full range = +/- 5 V
- frequency range:
  - d.c. (I-V, critical current)
  - 1 Hz to 1 kHz (resistivity, Hall)
- Low noise voltage read back: ~1 nV/rt-Hz on gain 1000 (high gain amp HGA) for a.c. signals
  - input impedance at x1000 is ~10 kOhm, very low!
  - for x1, x10, x100 (PGA) input impedance is ~ MOhm
  - see table 3-2 in ACT User Manual to explain gain stages
- common mode rejection 120 dB (100 dB) for HGA (PGA)
- Relays to multiplex for 2 channels
- **Optimized for relatively low resistances**
  - Best accuracy for R<100 Ω

Electrical Transport Option (ETO) hardware

- CAN module CM-H
  - DSP (“the brains”)
  - 1x and 3x signal amplifier gain stages
  - BNC monitors for both channels
- remote head between module and PPMS
  - 2 current sources
  - 2 preamplifiers

ETO theory of operation

- resistance measurement identical to ACT
  - a.c. signal, digital lockin
- I-V: triangle waveform frequency is selectable
- new mode: dV/dI vs. I
  - differential resistance
  - a.c. current I_{ac} on top of bias current I_{dc}
    - $I = I_{dc} + I_{ac}$
  - probes local slope of I-V curve
- two regimes:
  - low-impedance: same as ACT, Resistivity
  - high-impedance: new regime, uses only 2 wires at sample

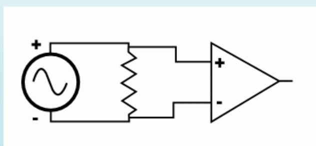
ETO measurement modes

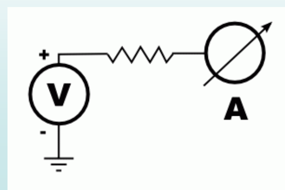
low impedance

- 10^{-8} to 10^{7} Ohm
- current source (10 nA-100 mA)
- voltmeter (1 nV - 5 V)
- **4-wire**
  - resistance
  - Hall
  - I-V
  - dV/dI vs. I

high impedance

- 10^{6} to 10^{9} Ohm
- voltage source (0.5 – 20 V)
- nano-ammeter (<250 nA)
- **2-wire**
  - resistance
  - I-V
  - dI/dV vs. V





Working on van der Pauw, which will be available only in low impedance mode.

ETO specifications

- frequency range: d.c., 0.1 Hz – 200 Hz
- common mode rejection: >100 dB (at gains above 10x)

4-wire mode

- preamp spec ~ 1 nV/rt-Hz
- sensitivity ~ 10 nΩ
  - from: 1 nV / 100 mA
- min. R ~ 10 μΩ
  - limited by ADC (90 mV / 5 V)
- max. R ~ 10 MΩ
  - current noise
  - parasitic capacitance

2-wire mode

- max. input current = 250 nA
- max source voltage = 20 V
- min. R ~ 2 MΩ
  - from: 0.5 V / 250 nA
- max. R ~ 5 GΩ
  - limited by leakage currents on PC boards

Electrical transport further reading

- *Low Level Measurements Handbook*, 6th edition, Keithley Instruments (2004) – free book from Keithley, very useful! http://www.keithley.com/pr/006.html
- *The Hall Effect and Related Phenomena*, E H Putley (1960)
- *Electrical Characterization of GaAs Materials and Devices*, David C Look (1989) (contact author for reprint)
- "A Method of Measuring Specific Resistivity and Hall Effect of Discs of Arbitrary Shape", L J van der Pauw, Philips Res. Repts **13**, 1-9 (1958)