Quantum Design electrical transport user training seminar

part 1: theory of operation

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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. 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)$^{1/2}$
    • 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 $\sim$ 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
• 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 $\omega$
  - 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 $V_\omega = \text{amplitude of } V(t) \text{ signal at } \omega$
  - boxcar averaging used (vs. running average in typical analog lock-in)
  - harmonic info is almost free, gives info on distortion of $V(t)$ signal

\[
V_\omega = \frac{2}{\pi} \int_0^{\omega/2} \sin(\omega t) \cdot V(t) \, dt
\]

\[
V_{N\omega} = \frac{2}{\pi} \int_0^{\omega/2} \sin(N\omega t) \cdot V(t) \, dt
\]
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** $\rho = R \times (\text{Area}/\text{Length})$
  - 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 $\rho$
  - 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)

<table>
<thead>
<tr>
<th>4-wire mode</th>
<th>2-wire mode</th>
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<tbody>
<tr>
<td>• preamp spec ~ 1 nV/rt-Hz</td>
<td>• max. input current = 250 nA</td>
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<tr>
<td>• sensitivity ~ 10 nΩ</td>
<td>• max source voltage = 20 V</td>
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<tr>
<td>– from: 1 nV / 100 mA</td>
<td>• min. R ~ 2 MΩ</td>
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<tr>
<td>• min. R ~ 10 μΩ</td>
<td>– from: 0.5 V / 250 nA</td>
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<tr>
<td>– limited by ADC (90 mV / 5 V)</td>
<td>• max. R ~ 5 GΩ</td>
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<tr>
<td>• max. R ~ 10 MΩ</td>
<td>– limited by leakage currents on PC boards</td>
</tr>
<tr>
<td>– current noise</td>
<td></td>
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<tr>
<td>– parasitic capacitance</td>
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Electrical transport further reading

- *Electrical Characterization of GaAs Materials and Devices*, David C Look (1989) (contact author for reprint)