

myDAQ-Compatible Curve Tracer Module for Introductory Electronics Laboratories

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Dr. David Beams came into the profession of electrical engineering through a passion for amateur radio during his days in high school. He earned the BSEE and MS degrees from the University of Illinois at Urbana-Champaign (1974 and 1977, respectively) and the PhD from the University of Wisconsin-Madison in 1997. He became a founding member of the faculty of the College of Engineering at the University of Texas at Tyler in 1997 and retired with the rank of Associate Professor from that same institution in 2018. He has a number of publications on topics related to engineering education and is particularly interested in the intersection of engineering and the creative arts. His 16 years in industry prior to joining academia underlie his interest in the transition from academic theory to industrial practice. He was formerly a licensed professional engineer in Wisconsin and Texas.

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The principal component of the introductory electronics course at the University of Texas at Tyler introduces students to the electrical characteristics of basic electronic devices (diodes, Zener diodes, MOSFETs, and BJTs). The accompanying laboratory includes experiments on measurement of the $I-V$ characteristics of these devices and derivation of small-signal models from those characteristics. Experimental procedures for measurement of $I-V$ characteristics have been in place at the University of Texas at Tyler for a number of years, but the development of “lab-in-a-box” solutions (such as the National Instruments myDAQ) has provided impetus to redesign these experiments to be compatible with that paradigm. To that end, the University of Texas at Tyler has designed a curve-tracer module that is compatible with the myDAQ and which allows students to make direct measurements of $I-V$ characteristics of diodes, Zener diodes, MOSFETs, and BJT using no ancillary equipment apart from the myDAQ (and host computer) and the device(s) under test. It is constructed with an inexpensive single-sided printed-circuit board and uses readily-available components. LabVIEW programs that automate the display of families of $I-V$ curves for MOSFETs and BJTs are under development. Complete schematic diagrams and PCB artwork are available for easy replication. This paper will describe the curve tracer, supporting programs, and examples of its application in the laboratory environment.

Introduction

The study of electronics is a core component of the electrical engineering curriculum. To the foundation of circuit analysis, the study of electronics introduces students to the principles of operation and electrical behavior of a number of electronic devices (principally the $p-n$ junction diode, the MOSFET, and the BJT). An understanding of the $I-V$ characteristics of these devices is indispensable to understanding their use in circuits exploiting them as either linear or nonlinear devices. While simulation is valuable, it is arguably not a replacement of the demonstration of the $I-V$ characteristics of real devices. A brief survey of ASEE literature on educational use of curve tracers is summarized below.

Shwehdi et al [1] described a senior design project to build an instrument for measurement of the current gain of NPN BJTs. This was not a curve tracer *per se*.

Beams [2] described curve tracers that used an *ad hoc* arrangement of GPIB-controlled laboratory instruments (dc power supply and digital multimeter) and LabVIEW virtual-instrument (VI) programs to measure the $I-V$ characteristics of $p-n$ junction diodes, NPN and PNP BJTs, and n -channel MOSFETs. Diode and MOSFET measurements required only an external resistor in addition to the laboratory instruments; BJT characteristics required an additional circuit to provide specified base currents. BJT measurements included both common-emitter and common-base connections. The chief drawback of this system was that measurement speed limited by the response of the GPIB instruments

A project to design and implement a LabVIEW interface for the Tektronix 370 curve tracer was described in [3]. The Tektronix 370 was a complex instrument that was difficult for undergraduates to master quickly; this project was designed to simplify the task of setting up and using the Tektronix 370 for a limited repertoire of measurements (basic diode measurements, common-source characteristics of MOSFETs, and common-emitter characteristics of BJTs). The project met with student acceptance, and it was integrated into the curriculum at the authors' institution.

Porter and Brannaka [4] developed a curve tracer using LabVIEW Signal Express and an external PNP current mirror circuit to construct a curve tracer for NPN BJTs.

Guran-Postelwaite et al [5] developed a web-based interface for remote laboratory use. Their developments included a method for measuring closed-loop gain and input impedance of operational amplifier circuits and an MOSFET curve tracer. Drain current of the MOSFET was measured by means of a transresistance amplifier. The design appears to support only NMOS devices.

Beams and Ochoa [6] described a curve tracer for diodes, MOSFETs, and BJTs that employed an external three-output dc power supply, signal generator, and a digital sampling oscilloscope. This design permitted collector/drain currents up to 35mA and collector/drain voltages up to $\pm 25V$. A Howland voltage-controlled current source was used to supply base currents for BJTs and collector/drain currents were measured with a transresistance amplifier.

An on-line search for curve tracers reveals various hobbyist designs, but few commercial products. An example of a commercial product for BJTs and FETs is described in [7]. Examples of hobbyist designs are found in [8]-[10].

Rationale for a new curve tracer design

The relevance of the curve tracer to the undergraduate electronics curriculum is apparent. However, the development of "lab-in-a-box" systems has fundamentally altered the paradigm of the undergraduate electronics laboratory; these devices (e.g., National Instruments myDAQ) allow the locus of laboratory work to shift from scheduled hours in the campus laboratory to any suitable time and venue (e.g., apartment, dormitory, laundromat, coffee shop). None of the commercial or hobbyist designs surveyed were suitable for this paradigm. A curve tracer for this environment must have sufficient performance to provide students with meaningful experience while requiring no external apparatus other than the "lab-in-a-box" and the device(s) under test. The curve tracer must be compact, inexpensive, easy to duplicate, electrically compatible with the "lab-in-a-box" system, and sufficiently rugged to withstand the rigors of casual handling and the dangers lurking in students' backpacks.

The design described in the next section was created specifically to meet these requirements and to be compatible with the myDAQ. The myDAQ provides dc power supply voltages of $\pm 15V$ at up to 32mA. It includes two differential analog inputs (designated AI0 and AI1) with 16-bit resolution and full-scale ranges of $\pm 10.00V$. The myDAQ provides two analog outputs (AO0 and AO1) with ranges of $\pm 10.00V$ and 16-bit resolution. Software provided with the myDAQ

includes a suite of virtual instruments including a two-channel oscilloscope, function generator, and dc output.

Brief description of the curve tracer circuit

The myDAQ and its associated virtual instruments can provide the external signals and measurement systems required by the curve tracer described by Beams and Ochoa ⁶. However, the $\pm 15V$ supplies of the myDAQ cannot deliver the supply voltages and currents for that curve tracer. The new curve tracer design therefore uses a hardware topology very similar to the Beams/Ochoa design, but with some reductions in output voltages and currents commensurate with limitations of the myDAQ power supplies.

The hardware topology of the curve tracer closely follows that described in [6]. The schematic diagram (drawn with National Instruments Multisim 14.0) is shown in Fig. 1 below. The 2N3904 NPN device labeled QTEST in Fig. 1 is not part of the curve tracer *per se*. It is a device included for simulation of the curve tracer circuit.

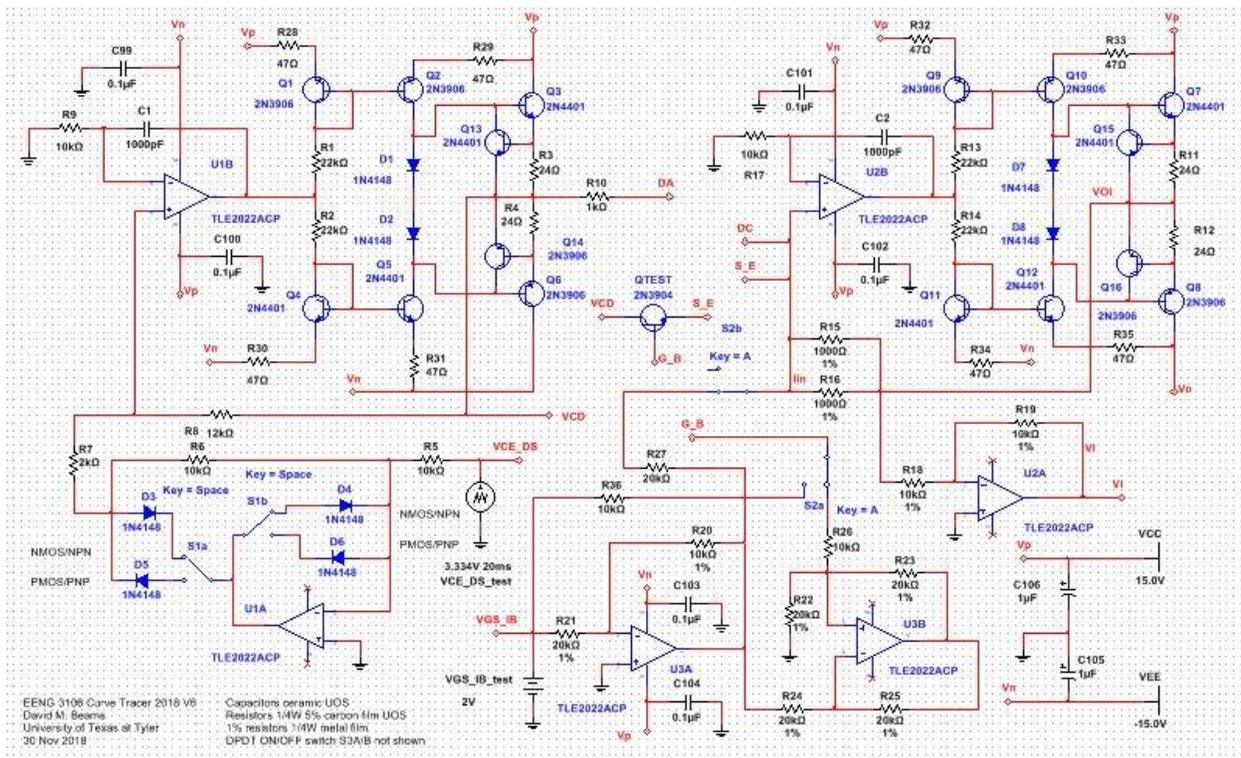


Fig. 1. Complete Multisim schematic diagram of the myDAQ-compatible curve tracer.

Figure 2 shows the schematic diagram partitioned into functional blocks.

Block A contains a precision half-wave rectifier (with switchable polarity) and a voltage-controlled voltage source (VCVS). This circuit is controlled by an external triangle-wave generator connected to terminal VCE_DS. This may be implemented in practice by a function generator or by an analog output of the myDAQ. The output voltage of the VCVS appears at terminal VCD and is a half-wave rectified triangle which may be positive-going or negative-

going, depending upon the polarity selected by switch S1. This output of the VCVS provides the collector voltage for BJTs or drain voltage for MOSFETs. Resistor R10 is a built-in current-limiting resistor used with diode *IV* measurements. The anode of a diode under test is connected to terminal DA. The VCVS output current is limited to approximately $\pm 25\text{mA}$.

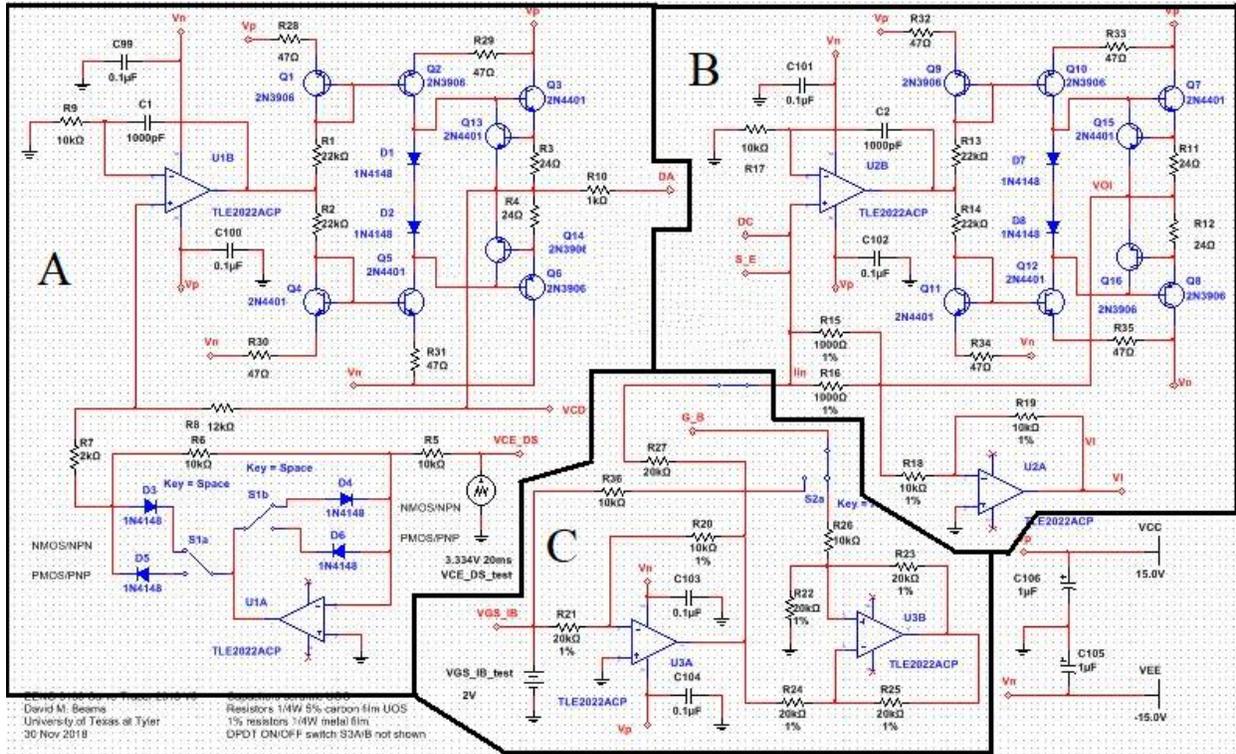


Fig. 2. Partitioned curve tracer schematic. Functions of each block are described in the text.

Block B is a transresistance amplifier that produces a voltage at terminal VI that is proportional to the current entering the virtual-ground input (terminals S_E and DC). The transresistance is $0.5\text{V}/\text{mA}$. Terminal S_E is connected to the source when the DUT is a MOSFET or to the emitter when the DUT is a BJT. Terminal DC is connected to the cathode when the DUT is a diode.

Block C is the circuit used to provide gate-to-source voltage when the DUT is a MOSFET or base current when the DUT is a BJT. Terminal G_B is connected to the gate when the DUT is a MOSFET or to the base when the DUT is a BJT. Switch S2 has determines the role played by this block. It has two positions; one is labeled MOS-D (used with MOSFETs and diodes) and the other is labeled BJT. With switch S2 in its MOS-D position, the voltage of external source connected to terminal VGS_IB is connected directly to the gate of the MOSFET test device. When S2 is in its BJT position, the voltage controls a Howland current source that provides a base current of $25\mu\text{A}/\text{V}$ to the test device. As noted above, when a BJT is the test device, its emitter is connected to the input terminal of the transresistance amplifier, and the output voltage of the transresistance amplifier would be proportional to the emitter current of the BJT. To read the collector current from the transresistance amplifier, a compensating current (equal to the base

current, but of opposite polarity) is injected into the input of the transresistance amplifier when S2 is in the BJT position.

Figure 3 is a photograph of the completed curve tracer.



Fig. 3. Completed curve tracer connected to a myDAQ and to a test MOSFET (not shown). Connections to circuit terminals mentioned in the text (e.g., VCE_DS) are made at the screw-type terminal blocks at the periphery of the circuit board.

Connections to the myDAQ

Figure 4 shows connections between the curve tracer and the myDAQ used for all measurements. All terminals labeled GND on the circuit board are common, so only one connection between GND and AGND of the myDAQ is necessary.

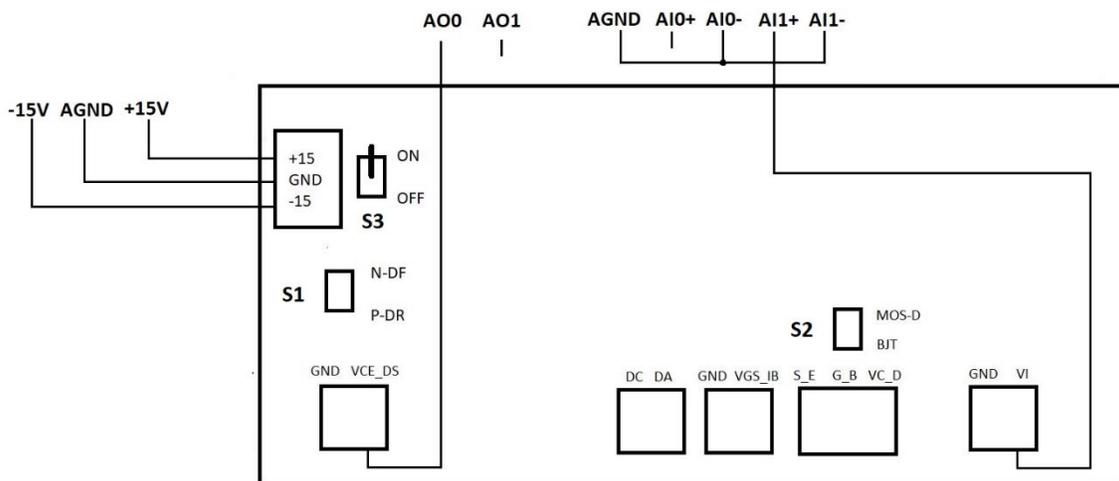


Fig. 4. Connections to the myDAQ used for all measurements. Analog output AO0 of the myDAQ is used to provide the triangle wave. Fully-differential analog inputs AI0 and AI1 are converted to single-ended inputs by connecting their inverting terminals (AI0- and AI1-) to analog ground AGND. AI1+ is connected to output terminal VI of the transresistance amplifier.

Figure 5 shows the additional connections necessary to measure the IV characteristics of a diode; Fig. 6 shows connections for a MOSFET, and Fig. 7 shows connections for a BJT.

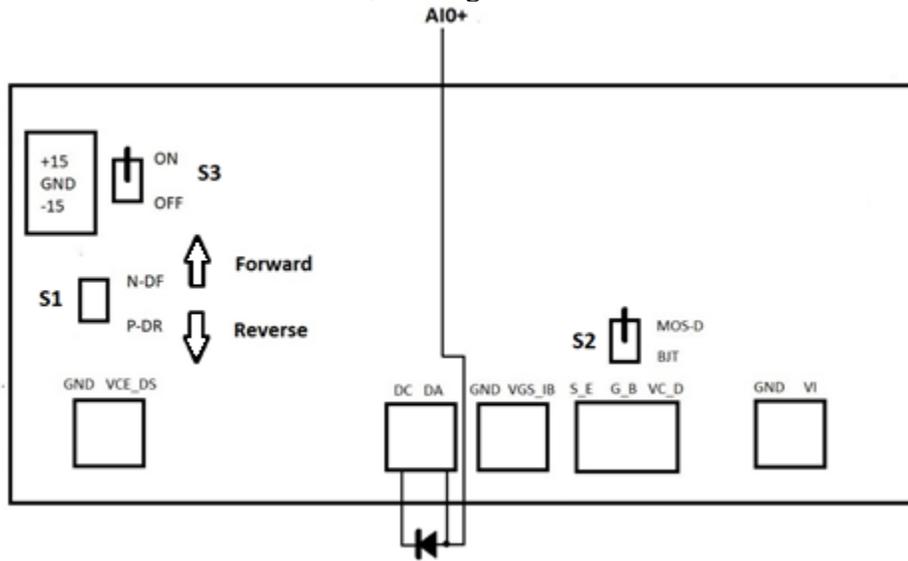


Fig. 5. Additional connections for measurement of the IV characteristics of a diode. Forward-biased characteristics are measured with S1 in the N-DF position; reverse-biased characteristics are measured with S1 in the P-DR position.

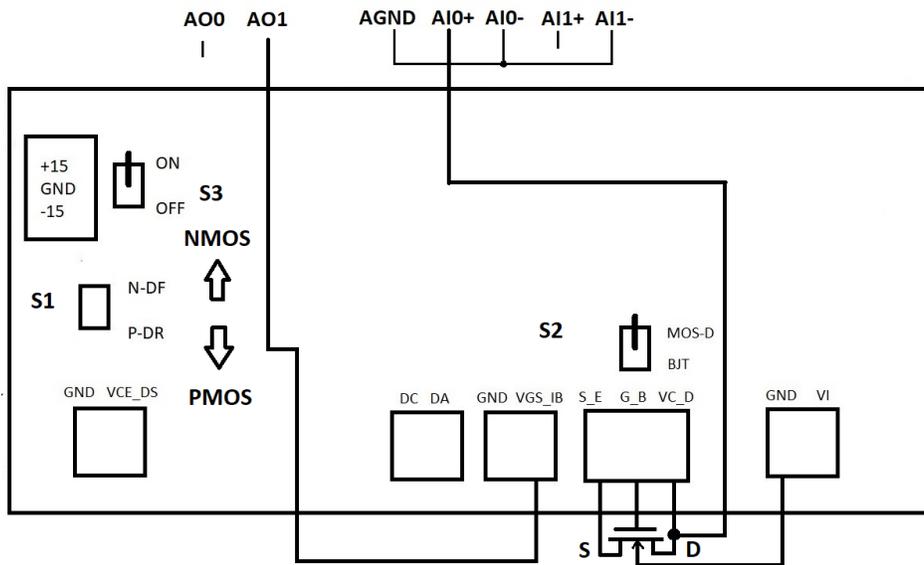


Fig. 6. Additional connections for the measurement of common-source IV characteristics of a MOSFET (NMOS device shown). Analog output AO1 provides the gate-to-source voltage of the MOSFET. The substrate terminal is to be connected to GND in the event that the MOSFET has separate source and substrate terminals. This connection is unnecessary if the source and substrate are internally connected.

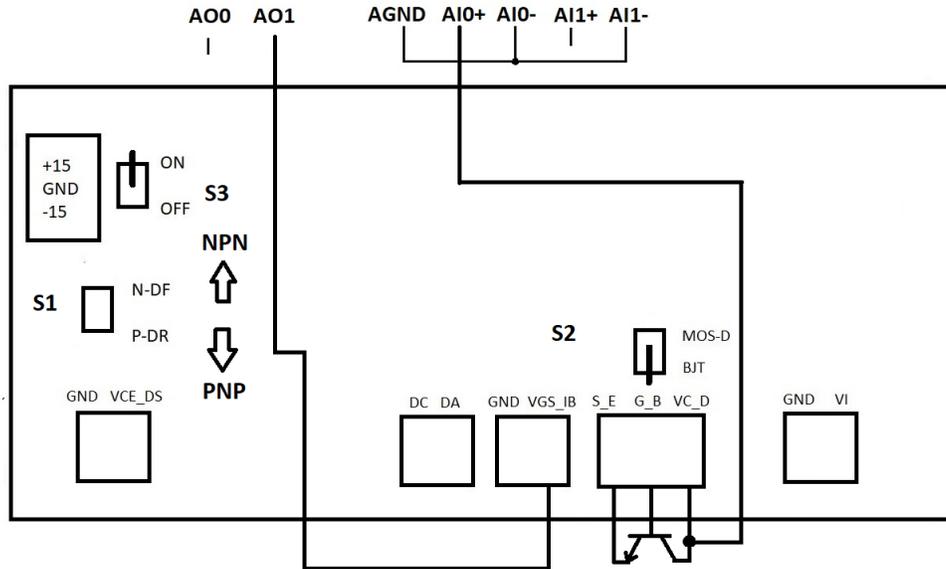


Fig. 7. Connections for measurement of the common-emitter *IV* characteristics of a BJT (NPN shown). Analog output AOO controls the base-current generator ($25\mu\text{A/V}$).

Example: diode *IV* characterization

Figure 8 shows myDAQ function generator settings and oscilloscope traces obtained with the curve tracer configured to measure the forward-biased *IV* characteristics of a 1N5231B Zener diode. Switch S1 of the curve tracer was in the N-DF position for these measurements. The connections from the myDAQ and the curve tracer are a composite of Figs. 4 and 5.

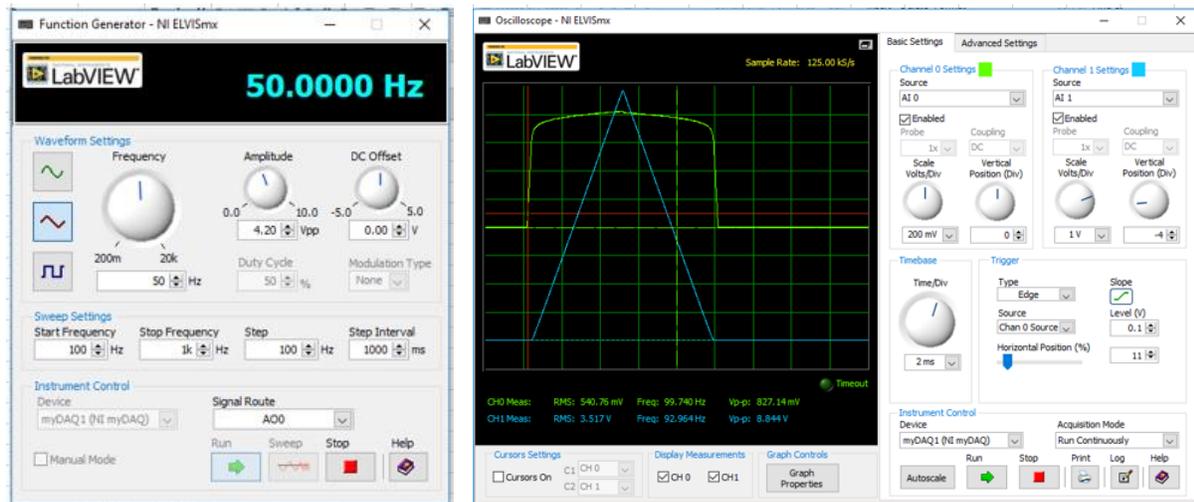


Fig. 8. myDAQ function generator settings and oscilloscope traces for forward-biased measurement for a 1N5231B Zener diode.

The voltage on Ch0 (measured by AI0) is the voltage at the anode of the diode. Since the cathode of the diode is connected to the transresistance amplifier's virtual ground, the voltage at

Ch0 is the diode voltage V_D . The voltage at Ch1 is the output voltage of the transresistance amplifier.

Pressing the STOP button of the oscilloscope halts data-taking and allows oscilloscope data to be written to a text file which may be opened for further analysis with Excel.

The oscilloscope channel voltages of the waveforms shown in Fig. 8 are replotted in Fig. 9 below. It is apparent from Fig. 9 that the diode voltage and current are zero for half of each measurement cycle. These data may be discarded. It is also apparent in Fig. 9 that the remaining data are symmetric about the instant when diode voltage and current reach their peaks. Thus the complete IV data may be found from either the increasing half or the decreasing half of the waveforms of Fig. 9. Manual parsing to extract the relevant data is somewhat tedious but not difficult. The exact range of data extracted is not critical as long as the complete IV data are contained therein.

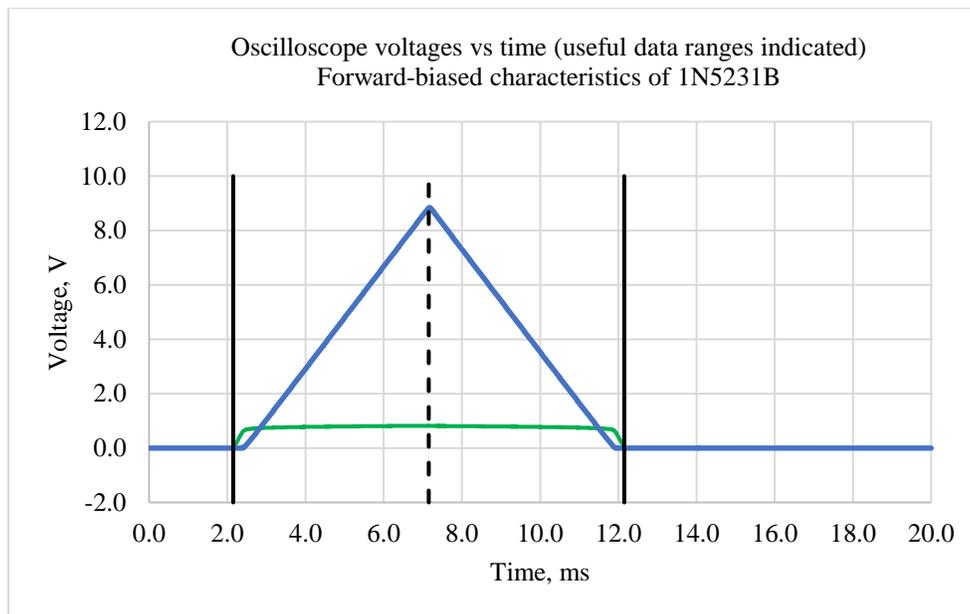


Fig. 9. Useful data ranges in the waveforms of Fig. 8. Complete IV data for the forward-biased are contained in two symmetric halves between the two solid vertical lines.

Figure 10 shows a sample of the Excel display of selected data from a myDAQ oscilloscope log file. The labels at the bottom have been added to identify the data in each column. A cursory examination of the data sample of Fig. 10 shows that the data were taken while voltages were rising toward their peak values.

waveform	Ch0		Gen
t0	00:06.9		00:06.9
delta t	8.00E-06		8.00E-06
time[0]	Ch0	time[1]	Gen
00:06.9	6.48E-01	00:06.9	3.86E-02
00:06.9	6.55E-01	00:06.9	4.56E-02
00:06.9	6.61E-01	00:06.9	5.55E-02
00:06.9	6.65E-01	00:06.9	6.84E-02
00:06.9	6.71E-01	00:06.9	7.96E-02
00:06.9	6.74E-01	00:06.9	9.02E-02
00:06.9	6.78E-01	00:06.9	1.00E-01
00:06.9	6.81E-01	00:06.9	1.13E-01
00:06.9	6.84E-01	00:06.9	1.28E-01
^ Timestamp ^	^ AI0 voltage ^	^ Timestamp ^	^ AI1 voltage ^

Fig. 10. An annotated sample of the data produced by the myDAQ oscilloscope during the forward-biased measurements of a 1N5231B Zener diode.

Timestamps are unnecessary for graphing current vs. voltage and may be discarded. The voltage at Ch1 is the output voltage of the transresistance amplifier. This voltage is the product of the diode current and the transresistance (500Ω) of the amplifier. Therefore, the diode current I_D may be computed from the Ch1 voltages by dividing by 500 (for currents in A) or multiplying by 2 (for currents in mA). Figure 11 shows the data sample of Fig. 10 after processing. Processed data may be graphed directly to produce the IV characteristic of the device.

VD, V		ID, mA
6.48E-01		7.71E-02
6.55E-01		9.12E-02
6.61E-01		1.11E-01
6.65E-01		1.37E-01
6.71E-01		1.59E-01
6.74E-01		1.80E-01
6.78E-01		2.00E-01
6.81E-01		2.25E-01
6.84E-01		2.56E-01
^ AI0 voltage ^		^ 2 x (AI1 voltage) ^

Fig. 11 Sample data of Fig. 10 processed for graphing of IV characteristics.

Figure 12 shows the oscilloscope display after moving S1 to the P-DR position. This reverses the polarity of the output voltage of the voltage amplifier (block A of Fig. 2). This setting is used to characterize the reverse-biased region of the diode IV curves.

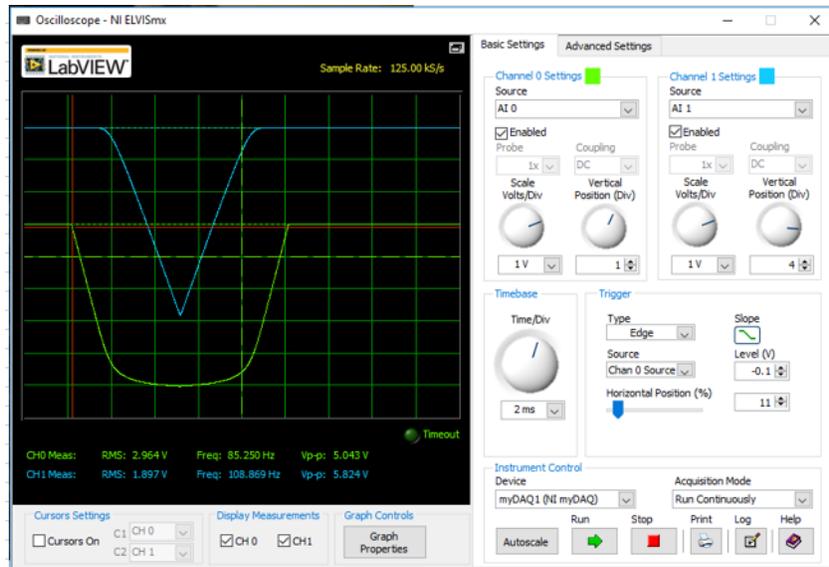


Fig. 12. Oscilloscope waveforms for the 1N5231B in reverse bias.

Data extracted from waveforms in Figs. 8 and 12 were used to create the composite IV curve shown in Fig. 13.

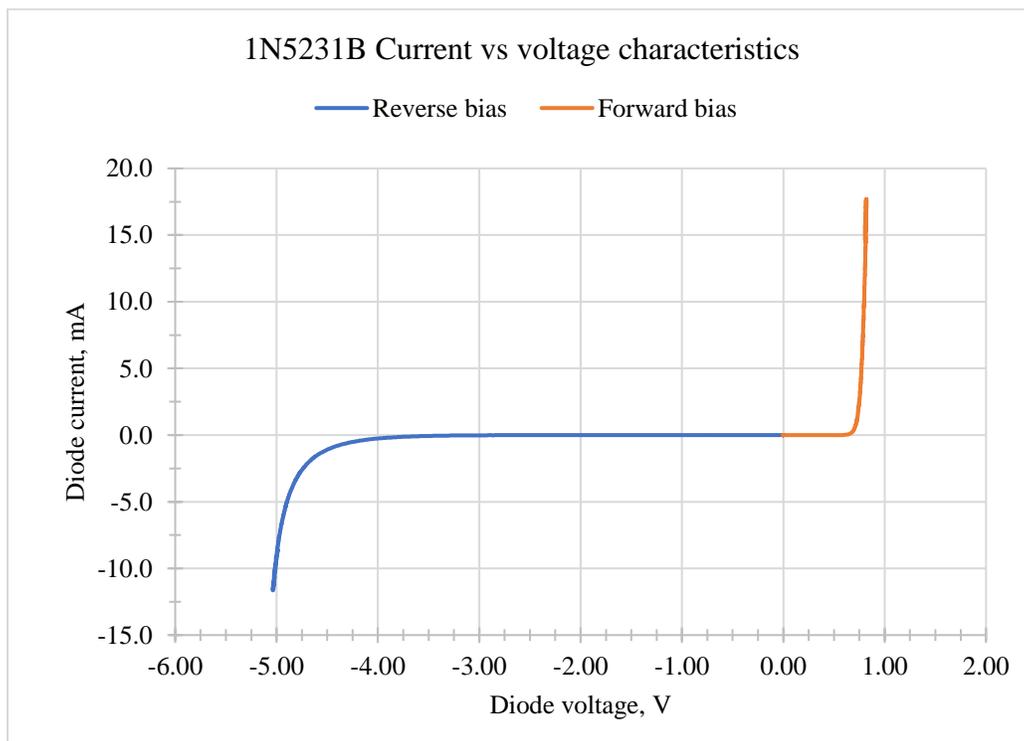


Fig. 13. Composite (forward and reverse-bias) IV data for the 1N5231B Zener diode

Example: MOSFET IV characteristics

Figure 14 shows instrument settings for measuring the common-source IV characteristics of an NMOS device. The connections of Fig. 6 are added to the basic connections of Fig. 4 for this analysis. The setting of S1 is N-DF and that of S2 is MOS-D. The myDAQ DC Level Output instrument is used to provide gate-to-source voltage V_{GS} . Figure 15 shows a composite family of characteristics for an ALD1106 NMOS device.

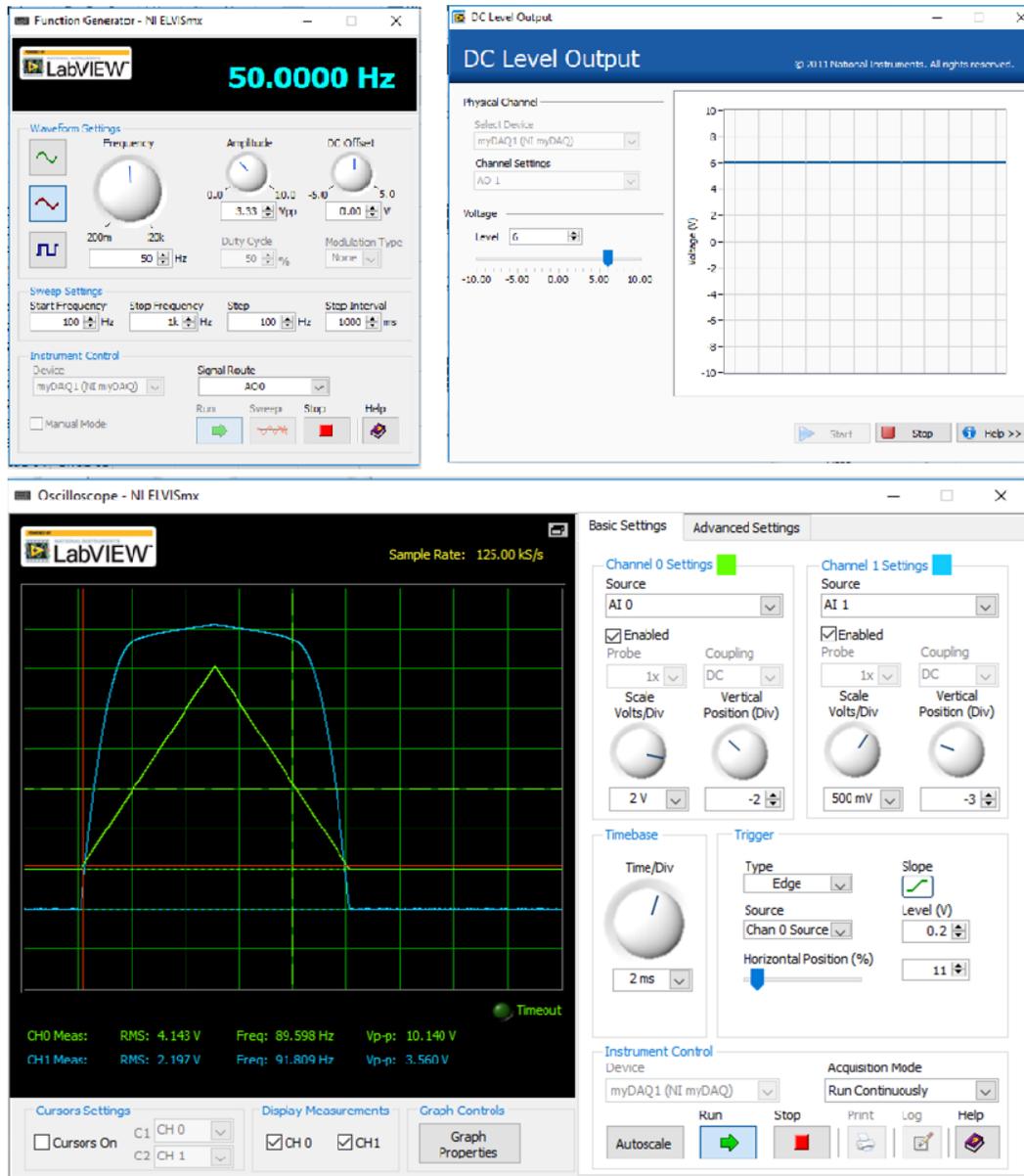


Fig. 14. Instrument settings and resulting oscilloscope waveforms for analysis of an ALD1106 NMOS device.

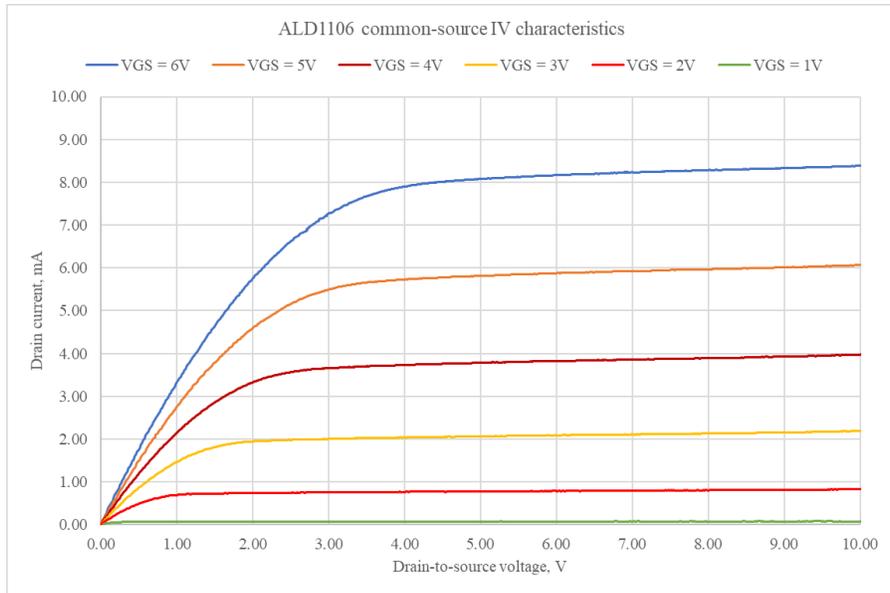


Fig. 15. *IV* characteristics for an ALD1106 NMOS device for gate-to-source voltages in increments of 1V from +1V to +6V. Triode and saturation operating regimes are evident, and the effect of channel-length modulation is apparent.

Measurement of the *IV* characteristics of a PMOS device is identical with measurement of NMOS characteristics except that S2 is set to P-DR and the gate-to-source voltage is negative. Figure 16 shows a composite family of curves for an ALD1107 PMOS device.

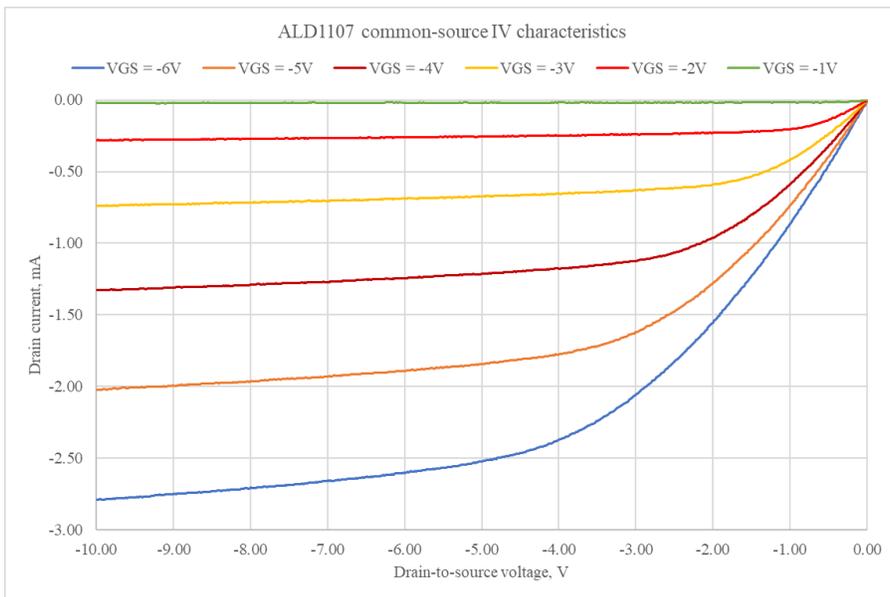


Fig. 16. *IV* characteristics for an ALD1107 PMOS device for gate-to-source voltages in increments of $-1V$ from $-1V$ to $-6V$. Comparison of Figs. 15 and 16 shows that the effect of channel-length modulation is more prominent in PMOS devices than NMOS.

Modeled drain currents may be fitted to measured data for extraction of model parameters. It is also possible to demonstrate the body effect in these devices by using an external adjustable voltage source to vary the substrate voltage. Figure 17 shows measured IV data for an ALD1107 PMOS device with source-to-substrate voltage $V_{SB} = 0V$ (no body effect) and $V_{SB} = -2.96V$ (including the body effect).

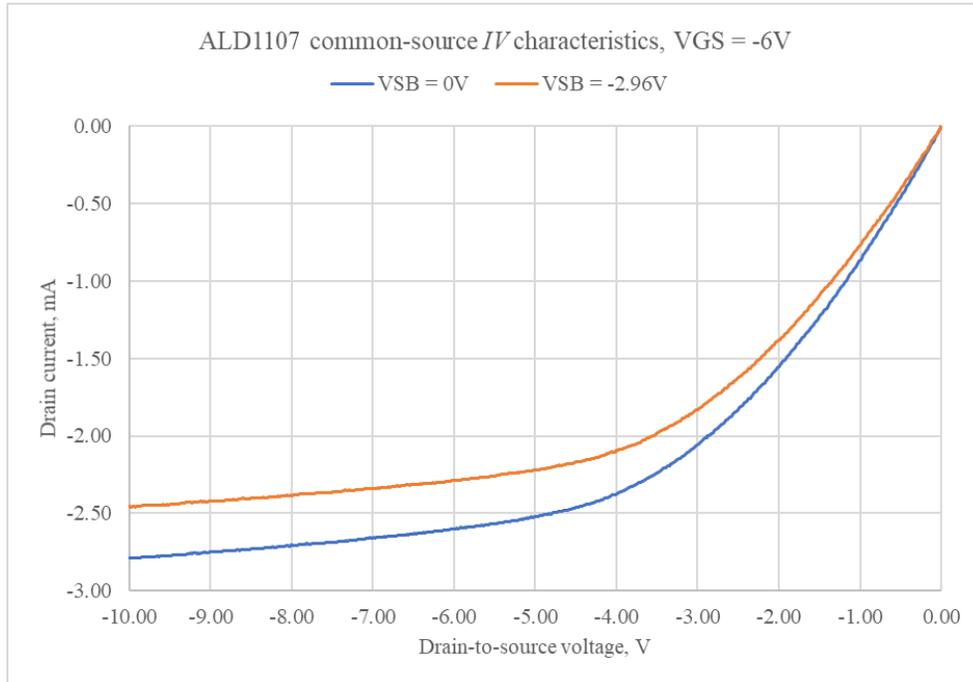


Fig. 17. Demonstration of the body effect on the common-source IV characteristics of an ALD1107 PMOS device. The substrate terminal of the device was elevated to $+2.96V$ by means of a resistive voltage divider across the myDAQ $+15VDC$ supply voltage.

Example: BJT IV characteristics

Figure 18 shows instrument settings for measuring the common-emitter IV characteristics of an NPN device. The connections of Fig. 7 are added to the basic connections of Fig. 4 for this analysis. The setting of S1 is N-DF and that of S2 is BJT. The myDAQ DC Level Output instrument is used to provide base current I_B with a transconductance of $25\mu A/V$. Figure 19 shows a composite family of characteristics for 2N4401 NPN device. The active and saturation regimes are easily discerned, and the Early effect is evident.

PNP devices may be measured in the same manner as NPN devices except that the position of S1 is P-DR and the voltage used to control the base current will be negative.

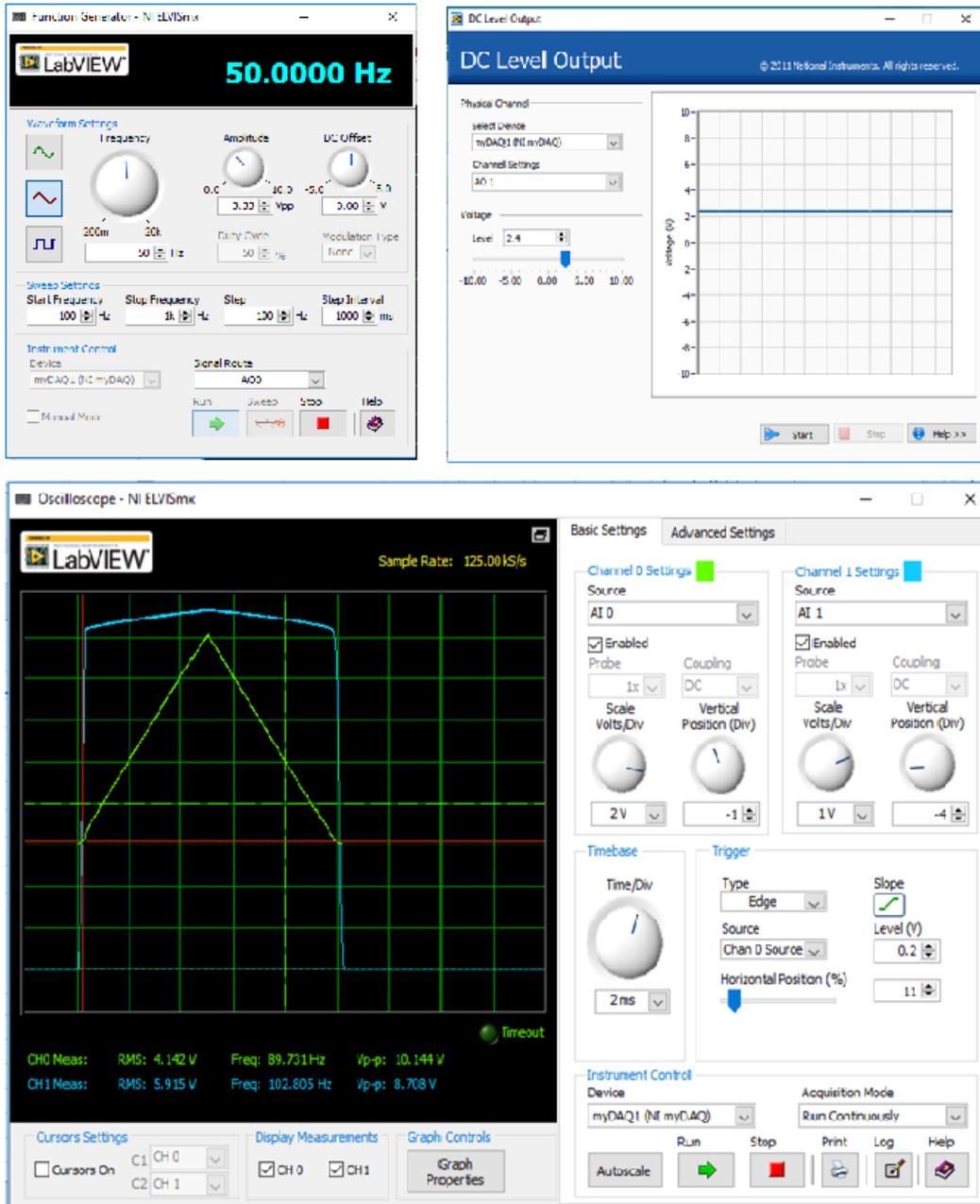


Fig. 18. Instrument settings and resulting oscilloscope waveforms for analysis of a 2N4401 NPN BJT.

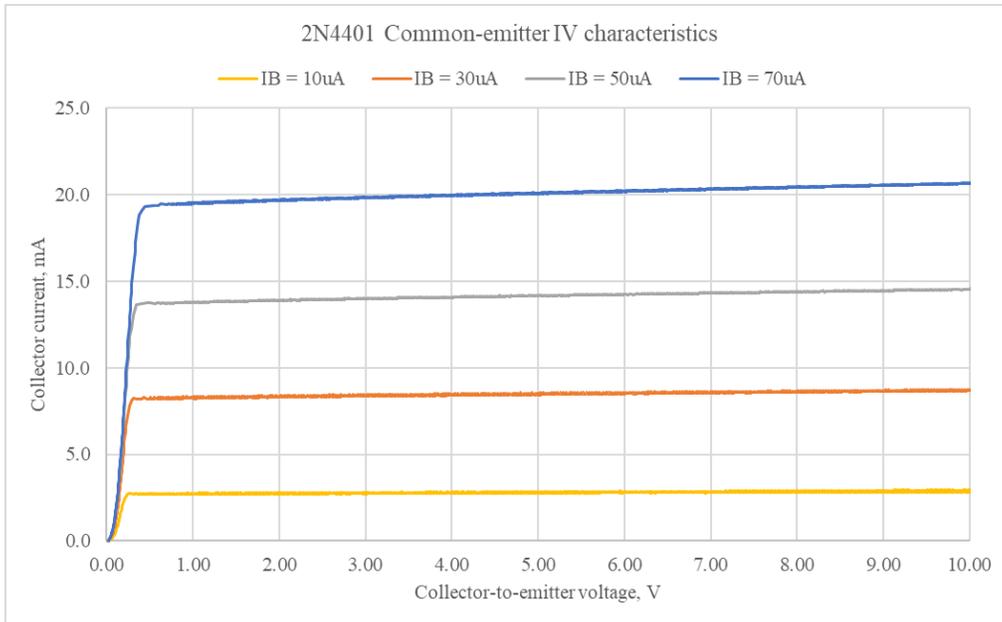


Fig. 19. *IV* characteristics for a 2N4401 NPN BJT for base currents in increments of $20\mu\text{A}$ from $10\mu\text{A}$ to $70\mu\text{A}$.

Virtual instruments for MOSFETs and BJTs

LabVIEW virtual instrument (VI) programs that produce families of *IV* characteristics (like the display of a traditional curve tracer) are under development. Figure 20 is copied from the LabVIEW front panel of the NMOS VI. The family of curves was produced by an ALD1106 NMOS device for a range of gate-to-source voltages from 0V to +6V in increments of 1V.

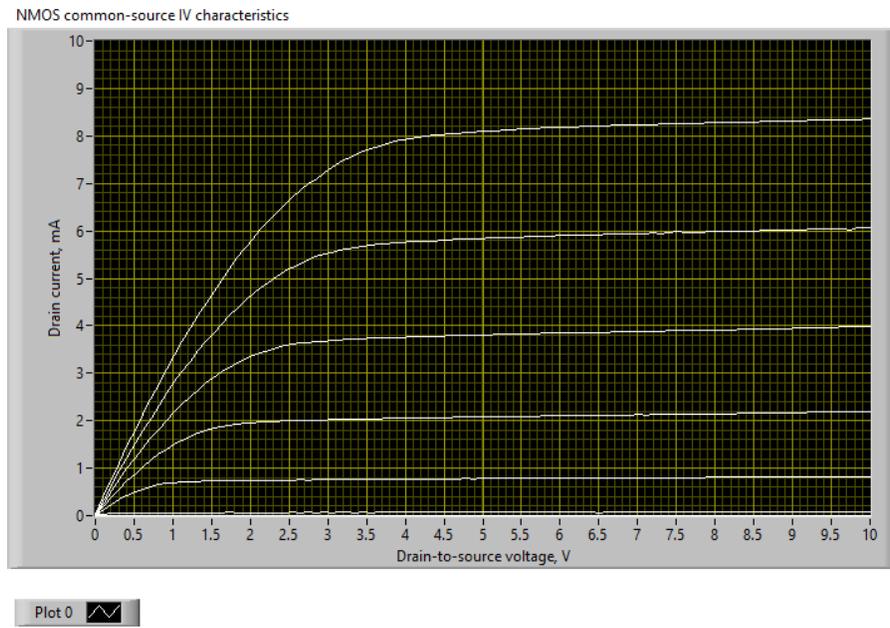


Fig. 20. Drain current vs. drain-to-source voltage characteristics of an ALD1106 NMOS device obtained with the prototype NMOS virtual instrument program.

Resources available for duplication of the curve tracer

This project's goals included the dissemination of documentation so that any school wishing to duplicate the curve tracer would have the resources to do so. The following resources are presently available:

- A Multisim 14.0 file of the schematic diagram;
- An Ultiboard 14.0 file of the PCB layout;
- Gerber files necessary for manufacture of the PCB;
- A complete parts list with vendor part numbers for all components.
- LabVIEW VIs for NMOS, PMOS, NPN, and PNP devices.

Laboratory procedures using the new curve tracer will also be available once they are updated.

Concluding remarks

The reader will note an adhesive label applied to the circuit board in Fig. 3. This label corrects an error in the labeling of the positions of switch S1. The silkscreen of the circuit board has been corrected.

The Howland current source used to generate base currents for BJTs has sometimes been observed to be unstable if long (> 30cm) leads are used to connect the BJT to the curve tracer. This is believed to be due to parasitic inductance of long leads. Short leads appear to cause no difficulties. It also been noted that the base-current generator could be stabilized if long leads are used by adding an 0.01 μ F ceramic capacitor between the base and emitter of the BJT under test.

This paper presents an inexpensive curve tracer module for determining the *IV* characteristics of common electronic devices. It is intended for use with introductory courses in electronics and is compatible with both standard laboratory equipment and with "lab-in-a-box" apparatus like the National Instruments myDAQ. It is hoped that this device will prove itself useful to a wide audience and be beneficial to students' understanding of basic electronic device characteristics.

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