An Inexpensive Curve Tracer for Introductory Electronics Laboratory Courses

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Among the fundamental topics of introductory electronics courses are the *I-V* characteristics of basic electronic devices—diodes, MOSFETs, and BJTs. However, the expense of a dedicated curve tracer would not be justifiable in an introductory electronics laboratory. An easy-to-operate device capable of obtaining the *I-V* characteristics of basic electronic devices would be highly beneficial, especially if it were sufficiently inexpensive and easy to construct that a curve tracer could be made available for each bench. The device described herein meets these requirements. Operating in conjunction with typical laboratory equipment (e.g, an oscilloscope with *x-y* display capability, a triangle-wave signal generator, and a triple-output dc power supply), it is capable of displaying the *I-V* characteristics of diodes, PMOS and NMOS devices, and NPN and PNP devices at device currents up to ±30mA and voltages up to ±24V (with an external ±25V power supply). It includes a voltage-controlled base-current generator for BJTs capable of ±300μA. Currents in the semiconductor device under test are converted to voltages by means of a transresistance amplifier. This paper will describe the circuit and its implementation as well as its curricular integration. Sample results from student work using these curve tracers is included.

Background and project rationale

A note to the reader: this paper does not contain groundbreaking developments in laboratory instrumentation. You will likely be disappointed if you are expecting a technological breakthrough, a *tour de force* that sweeps aside long-established paradigms in the undergraduate electronics laboratory. But if you are looking for a simple way to display the *IV* characteristics of basic semiconductor devices—if your expectations are sufficiently modest—we may have a solution for you! If this describes your motivations, we invite you to read on.

Various authors have confronted the problem of semiconductor curve tracing in the undergraduate electronics laboratory and have described their work in ASEE conferences. We thus turn to the work of those who have gone before, of the giants upon whose shoulders we propose to stand.

A curve-tracing system for *pn* diodes, NPN and PNP BJTs, and *n*-channel MOSFETs relied upon LabVIEW running on a desktop computer and laboratory instruments (power supply and voltmeter) communicating with the program through a GPIB (General-Purpose Instrument Bus) connection.[1] While the system was successfully integrated into the curriculum, it had the disadvantage of being rather slow, limited by the rate at which the GPIB instrumentation could be addressed. This slowness produced noticeable unintended consequences that altered the shape of the *I-V* curve due to self-heating of devices under test when significant device voltages and currents existed simultaneously in portions of the analysis.

A very simple published method [2] for tracing *IV* characteristics of diodes and common-emitter characteristics of NPN BJTs takes advantage of infinite-persistence capabilities of digital oscilloscopes. This technique requires only a low-frequency sinusoidal voltage source, a few resistors, and (in the case of the BJT), a dc power supply. The method appears somewhat cumbersome but does allow the display of families of curves (e.g., collector current vs. collector-to-emitter voltage for various base currents of the BJT).

A curve tracer for diodes was among the applications of laptop computers to the teaching of data-acquisition systems. [3] An even-simpler method for measuring *IV* curves of diodes requiring only a dc power supply, potentiometer, and two digital multimeters was outlined. [4] This method, however, required data to be recorded by hand for creation of the diode *IV* curve.

A LabVIEW interface communicating with a commercial curve tracer with GPIB capability (Sony/Tektronix 370) was developed and put into curricular use. [5] This LabVIEW interface greatly simplified the task of using this complex instrument and allowed the measurement of *IV* characteristics of diodes, PNP and NPN BJTs, and MOSFETs. The LabVIEW virtual instrument allowed the user to specify a quiescent operating point at which to determine the current gain β_F of a BJT or transconductance g_m of a MOSFET. This was among the most-powerful systems described in ASEE literature, but its implementation required ownership of an expensive commercial instrument and could only be used by one experimenter (or group of experimenters) at a time.

An intriguing web-based remote electronics laboratory was outlined. [6] This system includes experiments for determining the *IV* characteristics of the CD4007 MOS transistor array and extraction from these data of values for SPICE parameters VTO (threshold voltage), KP (transconductance parameter), and LAMBDA (channel-length modulation parameter).

Given the sweep of these developments, one may reasonably ask what justification there could possibly be for any further work in this area. But there reasons we believe cogent and convincing:

- There was a need for a device that could display *IV* curves of multiple types of semiconductor devices.
- Operation of the device should require only external instrumentation commonly found in introductory undergraduate laboratories.
- The device should not depend upon outdated technology (e.g., GPIB).
- The device should be sufficiently inexpensive that a number of units could be constructed and deployed in the laboratory to avoid students queuing up in the laboratory to use the curve tracer.
- The device must be sufficiently robust to handle the inevitable electrical misadventures to which it will be subjected at the hands of undergraduate students.

The design space of this project was constrained by these considerations. The following section gives the outlines of the design.

Circuit description and operation

Figure 1 below is a photograph of an example of the curve tracer. Mechanical support and packaging for the circuitry is provided by a housing of acrylic plastic. The chief reasons for choosing such packaging are that our institution has an abundance of such material in various thicknesses and has a small industrial laser that readily cuts it.

The curve tracer is not self-contained. It draws power from split dc power supplies of ±18V to ±35V. An independent adjustable voltage source is also required to provide the gate-to-source voltage V_{GS} of a MOSFET or control the base current I_B of a BJT. Our laboratory is equipped with Agilent E3631A triple-output power supplies which include split dc output voltages adjustable from 0V to ±25V and an independent voltage source adjustable from 0V to +6V. A signal generator and two-channel oscilloscope (with *x-y* display capability) are also required.

Connections to the device under test are made through terminal blocks. One terminal block contains the connections (E, B, C) for a BJT. A second terminal block has connections (S, G, D) for a MOSFET. The third terminal block makes available ±15VDC that may be used as substrate bias voltages when tracing the *IV* characteristics of MOSFETs that are part of transistor arrays (e.g., CD4007).

Two switches determine the functional mode of the curve tracer (MOSFET vs BJT, and NPN/NMOS vs PNP/PMOS).

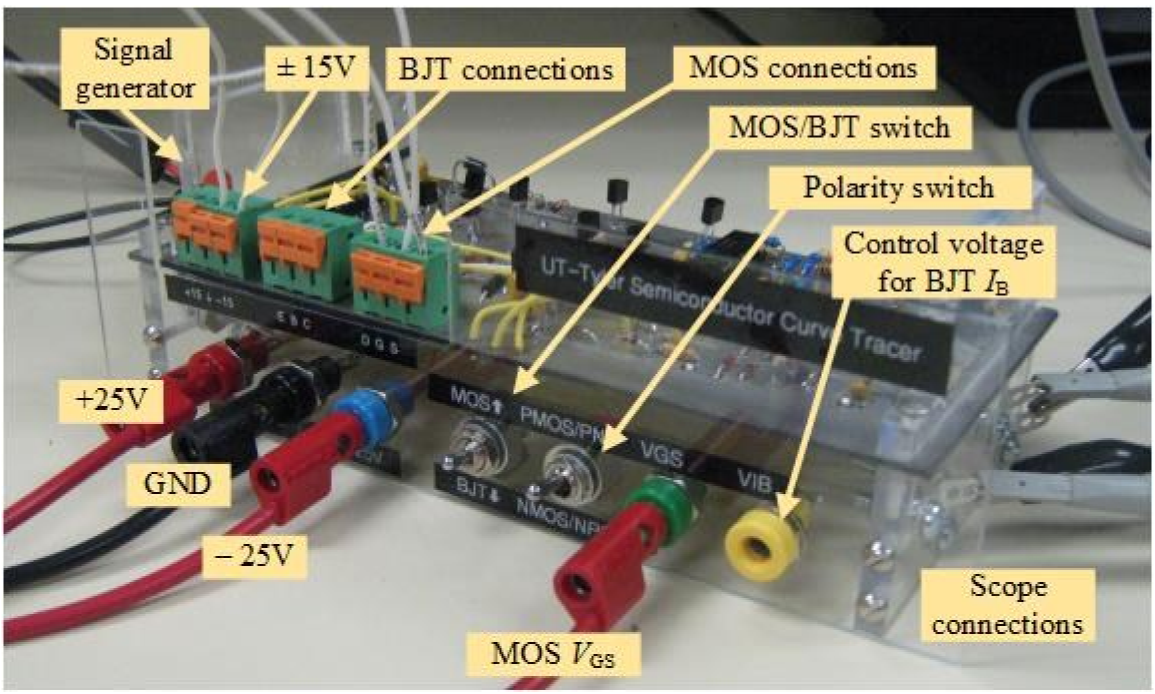

Fig. 1. Curve tracer front-panel connections. The unit is presently configured to measure the *I-V* characteristics of a PMOS device.

Figure 2 is a block diagram of the curve tracer. We have a complete schematic diagram of the device, but it is not included here. The schematic was drawn in landscape mode on an 11”×17” sheet, and shrinking the image to fit an 8.5”×11” sheet in portrait mode made the image unreadable. We will gladly provide a complete set of documentation to anyone who expresses an interest.

A triangle waveform provided by the external signal generator passes through a precision inverting half-wave rectifier. A switchable-gain (+1 or –1) amplifier determines the polarity (positive-going or negative-going) of the signal driving an inverting power amplifier. Grounding the gain-control terminal gives a gain of –1; leaving this terminal open-circuited produces +1. The output voltage of the power amplifier (which has a voltage gain of –10V/V) is applied to the collector contact of the BJT terminal block and the drain contact of the MOSFET terminal block. The amplitude of the signal generator determines the sweep of the collector/drain voltage. The output current of the voltage amplifier is limited to ±30mA. This is to prevent damage to the tracer when (not if) it is connected improperly.

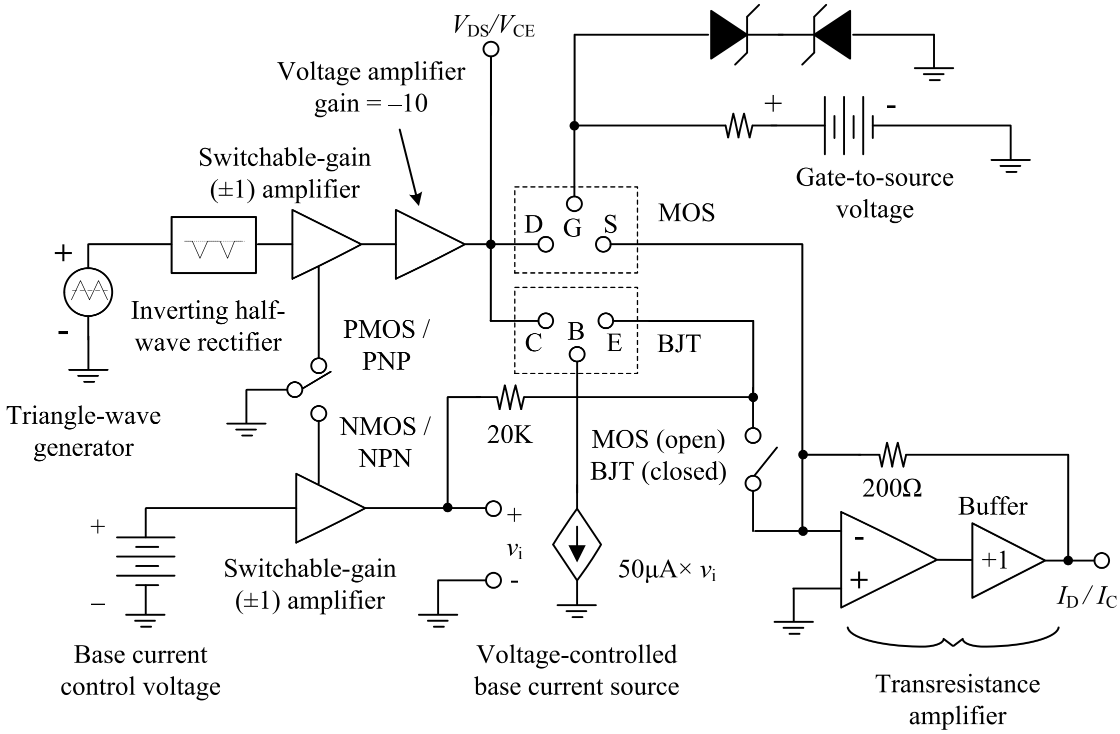

Fig. 2. Block diagram of the UT-Tyler semiconductor curve tracer

The source of a MOSFET under test is tied to the virtual ground summing terminal of a transresistance amplifier with a transresistance of –200Ω. Thus drain current I_D produces an output voltage from the transresistance amplifier of –200 I_D and the virtual ground at the source terminal makes the drain voltage (output voltage of the power amplifier) identical to drain-to-source voltage V_{DS}. The output current of the transresistance amplifier is limited to ±30mA. This is to protect the tracer from damage from inevitable accidental misuse.

The gate-to-source voltage V_{GS} is determined by an external dc source. The zener diodes limit V_{GS} to approximately ±7.5V and are included to protect the MOSFET under test by limiting the voltage that may appear at its gate. These diodes should never conduct in normal usage.

The MOSFET/BJT switch is closed when the characteristics of BJTs are measured. The BJT test circuits include a precision base-current generator whose output current is controlled by the voltage v_i in Fig. 2 with a transconductance of –50μA/V. (We assume the base current has a positive sign if it is flowing into the base terminal of the BJT). Voltage v_i is the output voltage of a switchable-gain amplifier (voltage gain of +1 or –1) whose input voltage is provided by an external dc source. Switching polarity from NPN to PNP will reverse the direction of base current without the necessity of changing the polarity of the external control voltage.

The emitter of the BJT is connected to the virtual ground summing node of the transresistance amplifier. The current entering this node from the BJT is the emitter current I_E. However, the common-emitter characteristics of the BJT plot collector current I_C vs. collector-to-emitter voltage V_{CE}. When the MOSFET/BJT switch is closed, voltage v_i appears across the 20K resistance in Fig. 2 and a current of 50μA × v_i is injected into the summing node of the transresistance amplifier. This current compensates for the base current component of I_E; thus the output voltage of the transresistance amplifier is –200 I_C.

The curve tracer is protected against accidental (but inevitable) reversal of the external power-supply connections. However, the one Achilles' heel of the design is in the ±15V outputs; these do not have their own current-limiting circuits and depend instead on current-limiting from the external power supply to protect them.

The curve tracer is fabricated on a double-sided printed circuit board developed with National Instruments' Ultiboard board-design software. Board-fabrication files in Gerber format are available. The cost of components in one example of the curve tracer is approximately $32. This does not include the circuit board and plastic housing which were manufactured in-house.

Curricular use of the curve tracer

There are three laboratory exercises in EENG 3106 (Electronic Circuit Analysis I Laboratory) which use the curve tracer. These are:

(1) measurement of I_D vs V_{DS} characteristics of PMOS and NMOS transistors;
(2) measurement of I_C vs V_{CE} characteristics of NPN and PNP small-signal transistors;
(3) measurement of *IV* characteristics of *p-n* junction diodes, including a small-signal silicon diode, a zener diode, and light-emitting diodes of various emission wavelengths;

- Measurement of I_D vs V_{DS} for MOSFETs

The CD4007 CMOS device includes an open-drain PMOS transistor, an open-drain NMOS transistor, and a CMOS inverter. As such, it provides an excellent vehicle for introducing students to the I_D vs V_{DS} characteristics of both PMOS and NMOS devices. (It is duly noted that the CD4007 is definitely not a leading-edge technology and its I_D vs V_{DS} characteristics are hardly representative of submicron devices. But examples of submicron devices where access to a single transistor is possible are not easy to obtain).

Students use the curve tracer to obtain CD4007 MOS I_D vs V_{DS} characteristics (for a range of V_{DS} from 0V to +15V for NMOS and 0V to –15V for PMOS) at various values of V_{GS}. Figure 3 shows the connections of a CD4007 to the tracer. The curve tracer provides the ±15V voltages shown in Fig. 3.

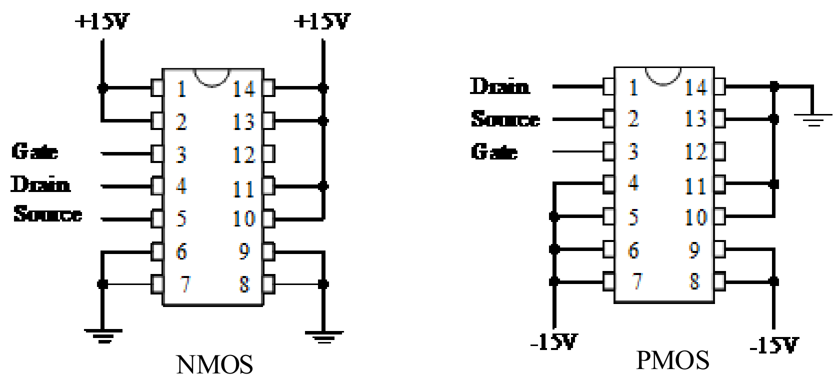

Fig. 3. Connections of the CD4007 to the curve tracer for measurement of MOSFET I_D vs V_{DS} characteristics. Pin 12 is left open-circuited. +15V, –15V, and ground are obtained from the dc supply terminals of the curve tracer.

In the laboratory procedure, waveform data are recorded with a digital sampling oscilloscope (DSO-X 2002A) and exported to external data storage in .CSV format, which may be opened with Excel. Figure 4 below shows a typical waveform record; the time base and triggering of the oscilloscope were adjusted to record the waveforms as V_{DS} is swept from 0 to its maximal value.

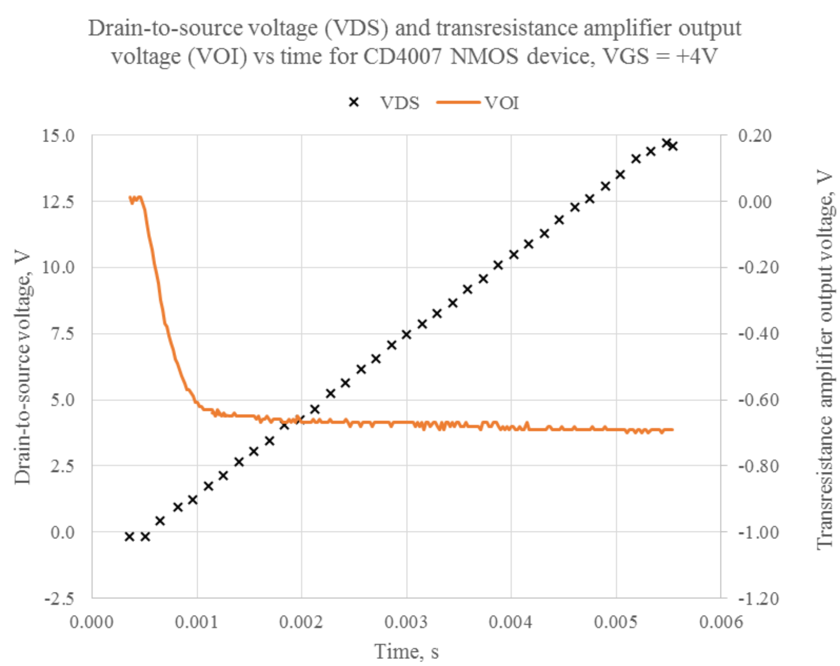

Fig. 4. Typical waveform record (traces vs. time) obtained with a digital sampling oscilloscope and the curve tracer.

To produce I_D vs. V_{DS} characteristics of a MOSFET, drain current I_D is computed from the output voltage of the transresistance amplifier and plotted vs. drain-to-source voltage V_{DS}. The laboratory procedure requires students to plot multiple I_D vs V_{DS} curves on a common set of axes to obtain the common-source characteristics of the device. Figure 5 is an example of complete CD4007 NMOS I_D vs V_{DS} characteristics obtained with the curve tracer and compiled into a single graph. Gate-to-source voltages here range from +1V to +6V in increments of 1V. V_{DS} and I_D data were recorded vs. time with a record length of 250 data points. Small dc offsets in both V_{DS} and I_D were subtracted and both waveforms were smoothed with four-tap FIR filters prior to being graphed.

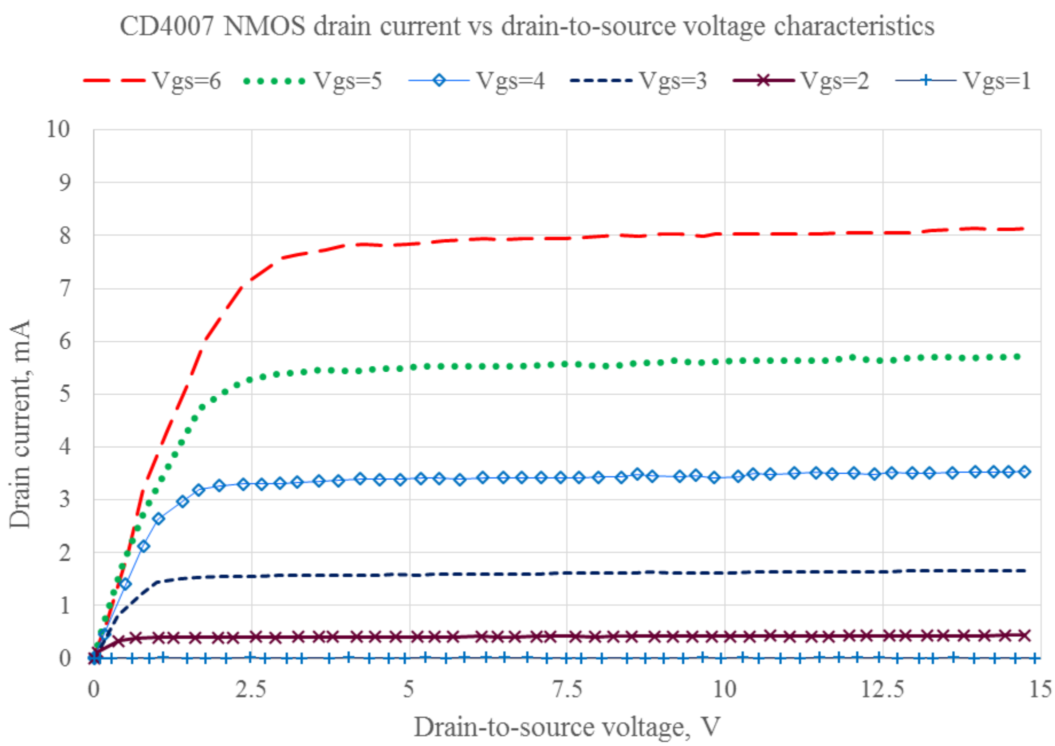

Fig. 5. Measured I_D vs V_{DS} characteristics of an NMOS device from the CD4007 MOS transistor array.

The threshold voltage V_t, transconductance parameter k_p', and channel-length modulation parameter λ of the MOSFETs may be estimated from measured I_D vs. V_{DS} characteristics by fitting data to the theoretical device equations:

$$I_D = k_p'\left(V_{OV}V_{DS} - \frac{1}{2}V_{DS}{}^2\right) \quad \text{(triode region, } V_{DS} \leq V_{OV}\text{)}$$

$$I_D = \frac{1}{2}k_p'(V_{OV})^2\,[1 + \lambda(V_{DS} - V_{OV})] \quad \text{(saturation region, } V_{DS} > V_{OV}\text{)}$$

where V_{OV} is the overdrive voltage $V_{GS} - V_t$.

Fitting the theoretical models to measured data for the CD4007 NMOS device with V_{GS} = 4V, 5V, and 6V yielded estimated parametric values: V_t = 1.10V, $k'_p = 0.676$mA/V^2, λ = 0.0065.

Figure 6 shows similar results obtained for the PMOS device of a CD4007. Again, the small dc offsets in V_{DS} and I_D were subtracted and data were processed through four-tap FIR digital filters prior to being graphed.

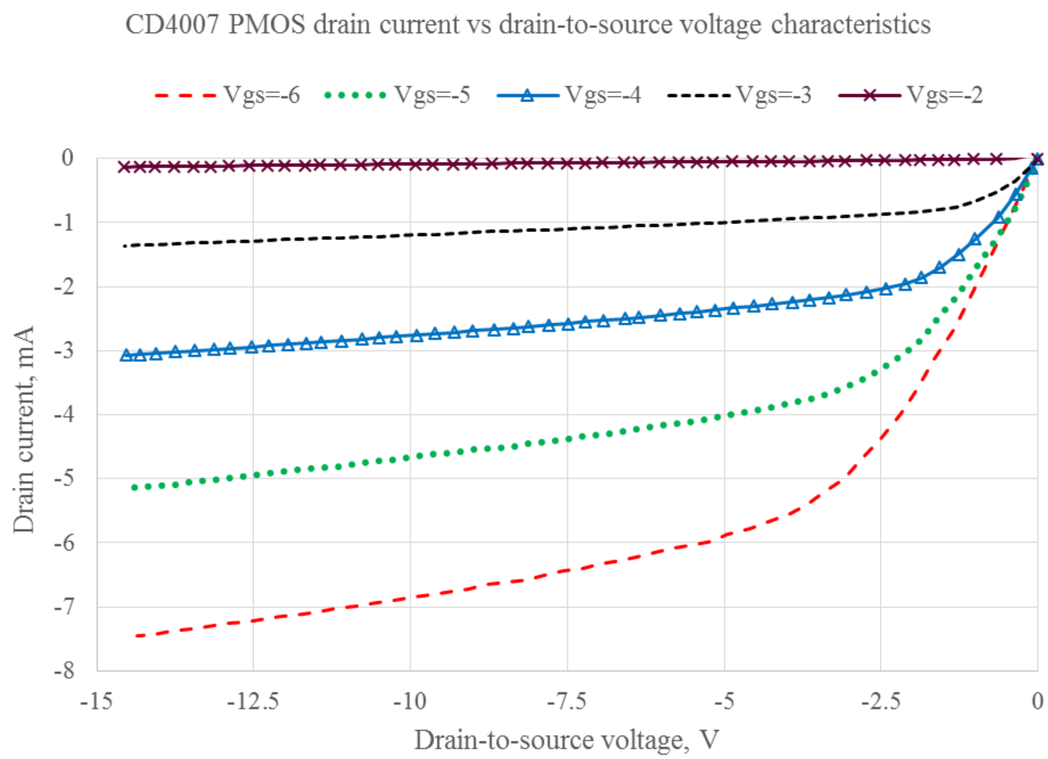

Fig. 6. Measured I_D vs V_{DS} characteristics of a PMOS device from the CD4007 MOS transistor array.

- Measurement of I_C vs V_{CE} in BJTs

Connections to the curve tracer for individual BJTs are straightforward and do not require use of the ±15V supplies of the curve tracer. Students take data of V_{CE} and the output voltage of the transresistance amplifier vs. time as V_{CE} is swept while base current I_B is held constant. This process is repeated for various values of I_B and the results are compiled to show the common-emitter characteristics of the BJT under test. Figure 7 is a composite image of common-emitter characteristics of a 2N4401 NPN BJT for base currents of 50μA, 100μA, and 150μA. Students can see quite clearly the sharp delineation between saturation and active regions of BJT operation and the effect of base-width modulation on I_C.

It should be noted that the curve tracer may be used to show directly the *IV* characteristics of the device under test if the oscilloscope is configured for *x-y* display. Figure 8 shows a screen image of the direct display of I_C vs. V_{CE} for a 2N3906 PNP BJT.

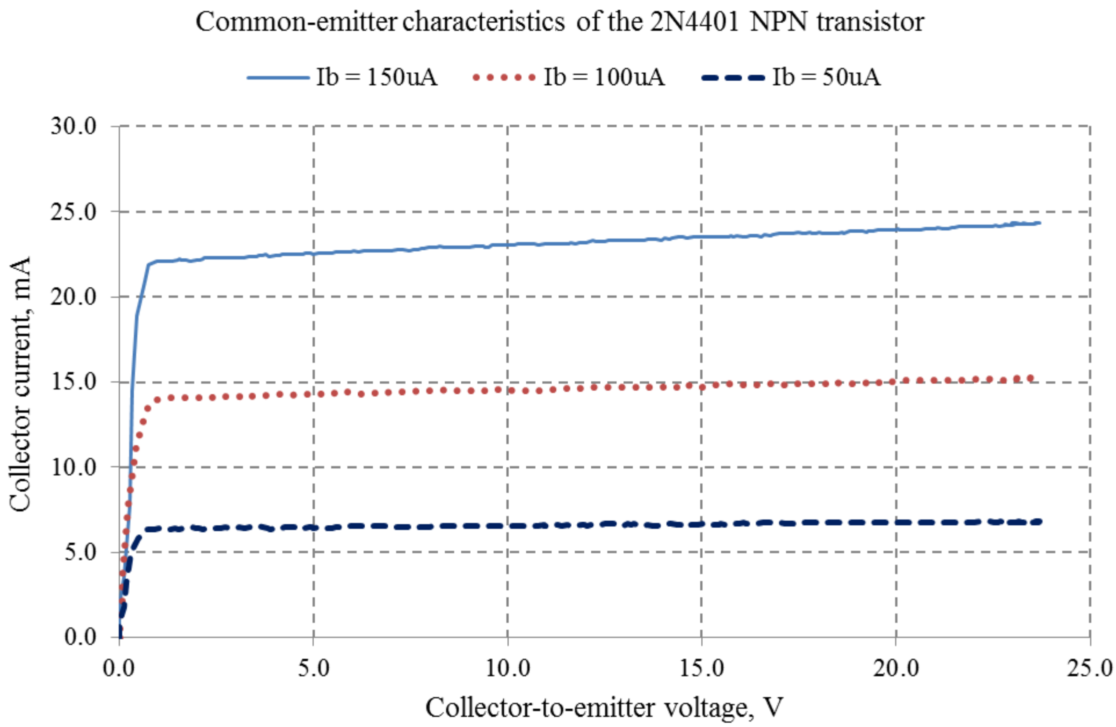

Fig. 7. Measured common-emitter characteristics of a 2N4401 NPN BJT. The small dc offsets in the curve tracer output voltages have been subtracted and both V_{CE} and I_C data have been filtered with 4-tap FIR digital filters.

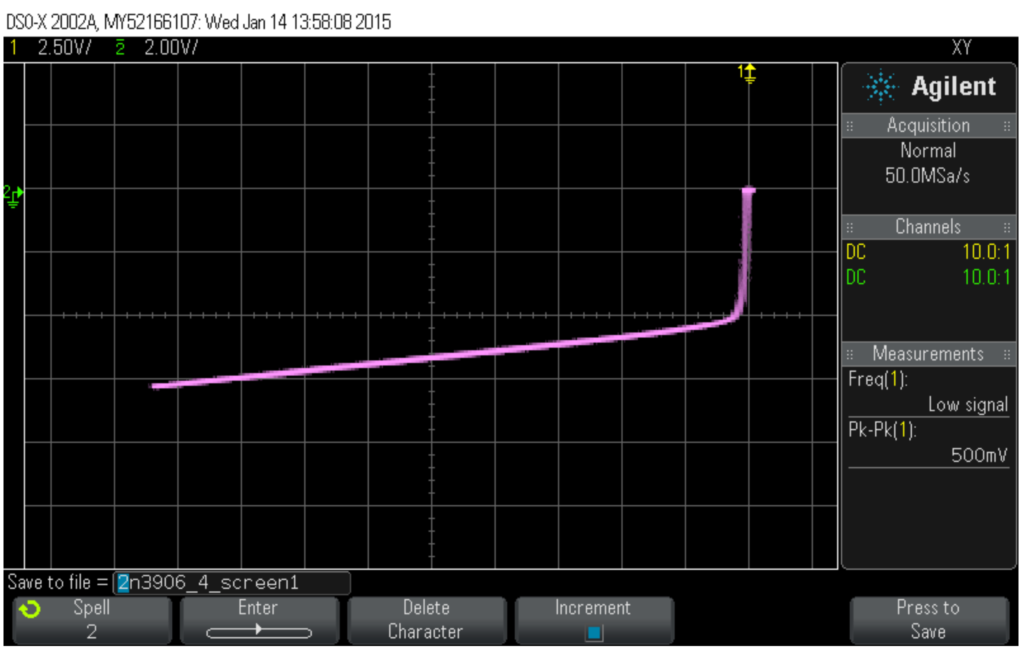

Fig. 8. Direct display of the I_C vs V_{CE} characteristics of a 2N3906 PNP BJT. Each vertical division represents 10mA and each horizontal division is 2.5V.

- Measurement of diode *IV* characteristics

The curve tracer is used in an experiment in which the *IV* characteristics are measured for various types of *pn* junction diodes (small-signal silicon diodes, LEDs of various emission wavelengths, and zener diodes). The configuration for measurement of the *IV* characteristics of diodes is shown in Fig. 9; it requires an external current-limiting resistance and diode voltage is measured directly at the anode terminal of the diode. The polarity switch of the tracer allows the polarity of the voltage applied to the diode and the current-limiting resistor to be reversed without reorienting the diode. A particular focus of the experiment performed in EENG 3106 is the relationship between the wavelength of emitted light and the forward potential of an LED for a given current.

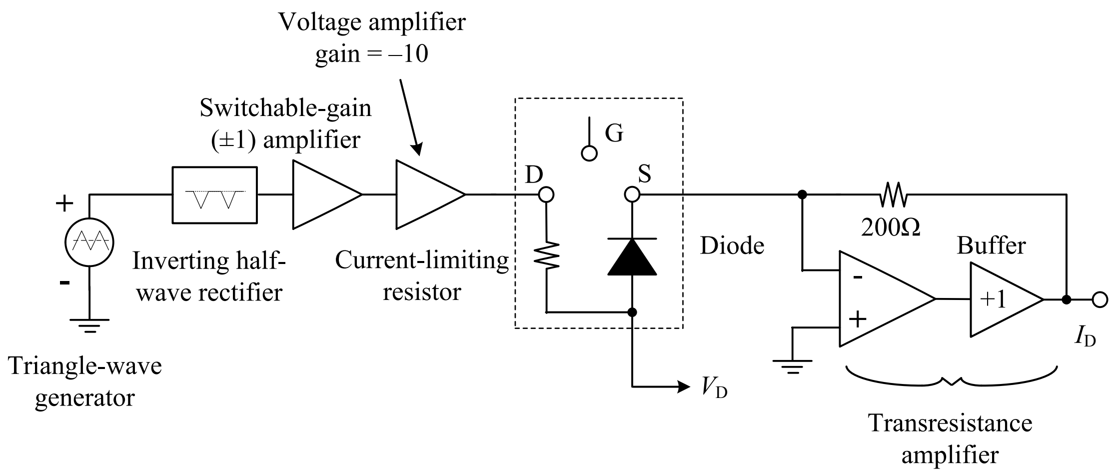

Fig. 9. Configuration for measuring *IV* characteristics of *pn* junction diodes. The D and S terminals of the MOSFET terminal block are used, and an external current-limiting resistor must be added.

Additional notes on external laboratory equipment

The question has been raised whether this curve tracer could be used in conjunction with a data-acquisition card and a LabVIEW virtual instrument (VI) instead of the signal generator and digital sampling oscilloscope mentioned in this paper. In principle, there would be no problems as long as the data-acquisition card could read voltages in the range of ±25V, generate a triangle wave of up to 5Vpp, and produce a dc voltage in the range of ±6V. However, this has not yet been attempted in the laboratory.

Conclusion

In the two years since the curve tracer was first introduced into EENG 3106, it has demonstrated its versatility and usefulness as a pedagogical tool. A total of 17 examples have been built and put into service in the introductory electronics laboratories of the University of Texas at Tyler, and several more are under construction at this writing. It has also demonstrated a gratifying measure of durability; all 17 examples are still in service at this time despite the rough treatment to which they are inevitably subjected.

References

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