# Simple Accurate Measurement of Semiconductor Device Conduction Characteristics using the Standard Undergraduate Laboratory Instrument Cluster

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**Abstract** The undergraduate lab in electronics is usually confined to a relatively simple cluster of instruments, usually centered around the oscilloscope and the waveform generator. In the undergraduate treatment of electronics the lab is the environment used to take a direct look at circuits which use real components and evaluate their wrinkles and vicissitudes. The first part of this closer look is to make an assessment of the conduction (current versus voltage) characteristics of semiconductor devices, usually diodes and transistors. This assessment is usually graphical. The oscilloscope is a natural and preferred vehicle for both visualization and measurement.

The principal difficulty with the conduction measurements is the fact that the nodes that must be used for assessment of current and voltage are contiguous but for display they must be separated. The usual technique is to add a resistance (as a linear component) to assess current. While it appears that this is a simple and direct process, it cannot be transferred to the display environment quite so readily. The fact that a dual-trace oscilloscope has a common ground for its two traces compromises its ability to separately provide a screen display measurement, whether time sweep or X-Y sweep.

The solution to this problem is to use an opamp as a means to make one node of the device under test (DUT) to be virtual, usually as a virtual ground. The opamp can then be used for an order-of-magnitude sampling switch for the measurement of current. The technique is clean and simple.

The technique can be applied to any device characterization or circuit characterization. Device conduction measurements for diodes (various types), bipolar-junction transistors, junction field-effect transistors, and MOS logic gates are represented. For purpose of the assessment of its conductance switching characteristics the MOS logic gate is treated as a pseudo-device.

*Keywords:* Undergraduate Laboratory, Semiconductor devices, Device characteristics, Measurement techniques

# I. INTRODUCTION

At the undergraduate level the first encounter with electronics as a subject area is as linear circuit elements, namely resistances, capacitances and inductances. These are all two-terminal devices. They each therefore become a path for the flow of current, either of the form of conduction current or of the form of signal current.

The framework for all circuits is therefore built up in terms of a set of branches connected at nodes, the branches being of the form of devices. The circuit is a network of nodes and branches. This network context forms the laws governing the circuit operation, namely that the sum of all currents into a node must = 0 and the sum of all voltages around a loop must add to zero. And in order to resolve the electrical situation that results, each branch, which is also a device, must be defined in terms of their current-voltage characteristics.

The Ohm's law relationship for resistance is the benchmark for all conducting devices. Circuit simulation software makes use of the linear equation $I = GV$ to describe any conduction path, whether a device or an interconnect. As long as the limits of operation are met and no irreversible damage occurs, then this is a reasonable baseline mathematical model.

The Ohm's law usage forms the basis for devices which are not quite as simple, such as the diode, for which the *I vs V* response is non-linear. It can be described [1] (to first order) by the equation

$$I_D = I_S\left(e^{V/nV_T} - 1\right) \tag{1-1}$$

Since the relationship is non-linear there is no longer an analytical solution, and the student then finds that simple networks are no longer simple and the words Newton-Raphson iteration becomes part of his/her vocabulary.

Of course the superposition of software is beneficial. For the more disciplinary approach usage of such tools as Matlab come to mind, and does give an appreciation of the process that circuit analysis software must undertake in order to present a reasonable resolution to the situation of currents through the network and voltages around the network. And when the process is extended to signals, for which it must, then time/frequency responsive elements such as capacitances and inductances are in order and the circuit analysis becomes a task of complex variable analysis and much extra Matlab usage.

Otherwise we avoid the disciplinary approach of Matlab and turn to a reasonably standard circuit simulation platform to handle the circuit analysis. At the undergraduate level and in many industry situations pSPICE is the usual favorite, and is the one referenced in this paper. It also provides a good graphics platform for circuit schematics, from which the node list is captured directly and for which a reasonable set of screen graphics is available through the postprocessor.

It becomes evident though this exposition that circuit analysis must either rely on a heavy use of software or on rough approximations. In the classroom rough approximations are the rule. They are the simplest approach and give a means to give a reasonable assessment of the situation. As the situation and time permits these can be followed up by simulations.

But for the ultimate snake-check these situations need to be taken to the lab and be subjected to a cluster of test instruments. Devices that are described by models are subject to mathematical caveats. Real devices and the circuits associated with them expose all vicissitudes.

## II. SCOPE OF THE MEASUREMENT PROBLEM

The typical measurement cluster for an undergraduate workstation consists of

(1) voltage-defined power supply, usually bipolar and variable from 0 – 20V.
(2) Digital Multimeter (DMM).
(3) Signal generator.
(4) Dual-channel 20Mhz Oscilloscope with *X(t), Y(t)* and *X-Y* display capability.

Higher end options are also available, usually with more functions and capability at higher frequencies.

The measurement instruments are usually buffered and compensated for minimal intrusion of the circuit or the device under test. Each of the sources usually has sufficiently low output resistance to offer minimum offset of the measurement signals. Assuming reasonable calibration, the oscilloscope forms a good measurement screen, and usually comes equipped with assistance features such as cursors and measurement capture.

But all instruments come with a ground and a measurement consequence results. The common ground provides a sneak path that can short out a measurement whenever more than one measurement must be undertaken concurrently. Better instruments may use a virtual ground but most are wired with a chassis ground for reasons of safety.

In the case of a device measurement, the desired measurement is *I vs V*. This is a concurrent measurement of two different electrical quantities. To accomplish such a measurement the device of interest is deployed in series with a resistance, and a voltage signal is placed across the series pair. Measurement of current is achieved by measurement of the voltage $V_R$ across the resistance, for which $I = V_R/R_1$. This is a practical and traditional technique. But it is usually done by hand as a point-by-point measurement using a DMM

If there is to be any reasonable throughput or accuracy the process needs to be put on screen via use of the oscilloscope. Not only does this give better measurement speed and accuracy, but measurements can (often) be downloaded into a database from the backplane, where they can be fitted against analytical models using conventional utilities such as spreadsheets.

However, the (two) channels of the oscilloscope are seldom independent of one another and usually have a common ground that is (also) the chassis ground. For the series pair of device and resistance a sneak path occurs when the voltage source from the signal generator is applied. Either the device or the resistance is shorted. The problem is illustrated by Figure 1(a).

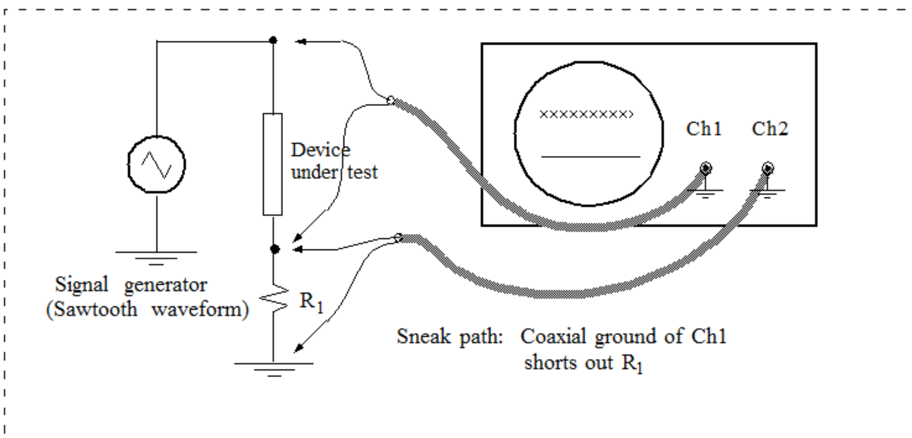


**Figure 1(a)** Sweep measurement sneak paths

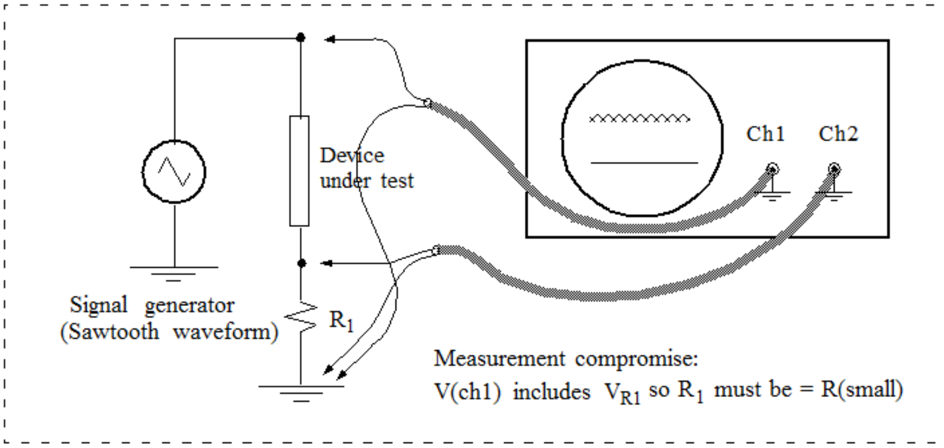


**Figure 1(b)** Compromise resolution of sneak path

Alternatively the resistance $R_A$ can be made very small, and can be accepted as either measurement offset or a compensation measurement can be made. This alternative is illustrated by Figure 1(b). It has a few caveats, inasmuch as the small resistance will only yield a small $V_R$, and the amplified signal will suffer from the noise factor of the measurement amplifier. The higher gain also may then amplify any parasitic signals that can sneak into the circuit though wiring antennae or through ground loops.

## III. Resolution via virtual connections

The solution to the sneak path is mildly subtle but also fairly obvious, and the technique might indeed be an internal caveat for instruments that are dedicated to the measurement of device characteristics. One of the troublesome ground nodes of Figure 1 needs to be made into a virtual ground. This option is readily achieved by insertion of an opamp into the measurement scheme. The option is illustrated by Figure 2. The most likely choice for the virtual connection would be that of the oscilloscope ground, as shown. Measurement of current is then taken from the output of the opamp. And with this scheme the feedback resistance $R_F$ also serves as a magnitude selection component for the current $I$ since $I = V_O/R_F$. If the currents are expected to be on the order of μA the resistance $R_F$ should be on the order of MΩ. This option is of considerable benefit when examining device characteristics in circumstances for which the current limits are either very high or very low with respect to higher voltage levels.

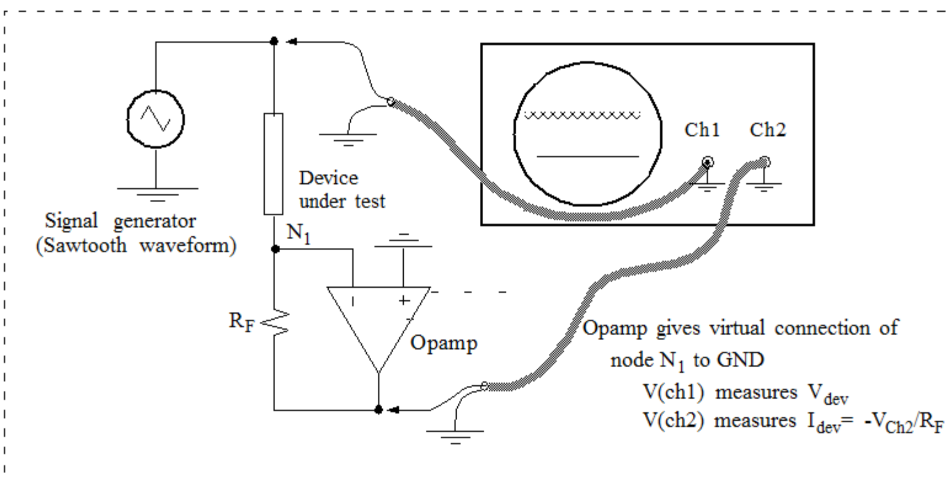


**Figure 2.** Device I-V measurements using a virtual ground. The inputs of the opamp are not connected, but are virtually the same courtesy of the high voltage gain of the opamp for which $(V_+ - V_-) = Vo/A_V$, where $A_V$ is usually on the order of $10^4$ V/V or higher.

The opamp is an inexpensive and simple component and does not add a great deal of overhead to the measurement schematic. A bipolar power supply (usually +- 12V) is necessary for activation of the opamp but is usually part of the measurement cluster and does not add any compromising sneak paths.

## IV. USAGE AND EXAMPLES

Measurement of device characteristics is a staple of the undergraduate laboratory in electronics. The devices of interest are usually the diode (various types) and the transistor (various types). If logic circuits are a part of the curriculum menu then logic gates may be added to the menu as a ‘device’.

In all instances for the labs described the uA741C general-purpose opamp was accepted as the added measurement element. This is a fairly robust BJT opamp that is able to withstand considerable abuse. As long as the measurement frequencies and amplitudes are kept low ($f$ < 50kHz, $V_{out}$ < 6V) the results are well-behaved. Most results are downloaded directly into a spreadsheet database, for which they are then curve-fitted to models of interest using screen menu options.

**(a) Measurement of diode conductance characteristics.**
Figure 3(a) shows the test setup. The resistances $R_1 = R_2$ define the level of current $I_D$ through the diode. It is desired that the exponential character [1] of the diode conduction characteristics be assessed (as indicated by Figure 3(b)) so $I$ vs $V$ measurements have need to be accomplished over several decade levels of current. Decade measure of current $I$ is set by decade magnitude selection of resistances $R_1 = R_2$. Parameters of interest are the reverse saturation current $I_S$ and the emission coefficient (also called the ideality factor) $n$. These are extracted by means of a logarithmic curve-fit of the data to the ideal diode equation using the spreadsheet.

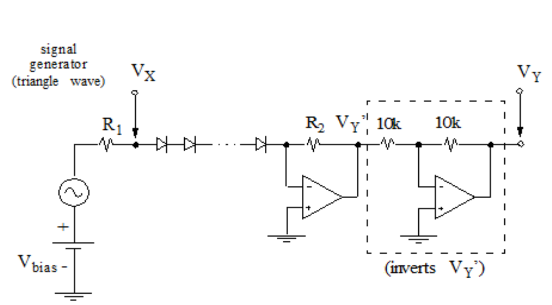


**Figure 3(a)** Diode test circuit

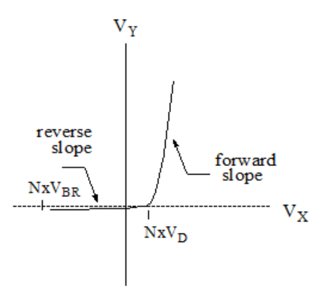


**Figure 3(b):** Output expectation

The inputs to the oscilloscope are set in the X-Y mode for which an output like Figure 3(b) should be expected.

Figure 3(c) shows a photo snapshot of the scope trace for this test setup. If the Oscilloscope is not equipped with access to the backplane then the instructions call for at least 3 data point measurements of $V_Y$ vs $V_X$ to be read using the measure (menu) option and then transcribed to a spreadsheet data base. The process is repeated for a succession of decade magnitudes in the current via sensing resistance $R_2$ . The spreadsheet is used to fit a logarithmic plot of measurements to the diode equation.

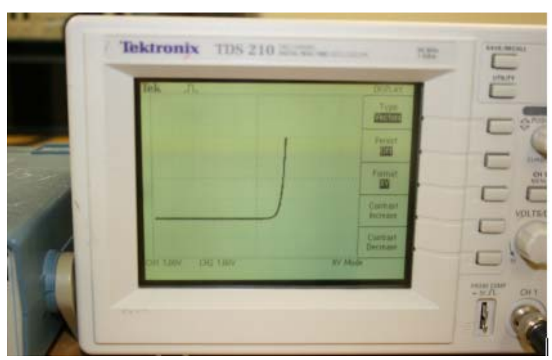


**Figure 3(c) .** XY output trace for the 3(a) test circuit

**(b) Measurement of transistor characteristics.**

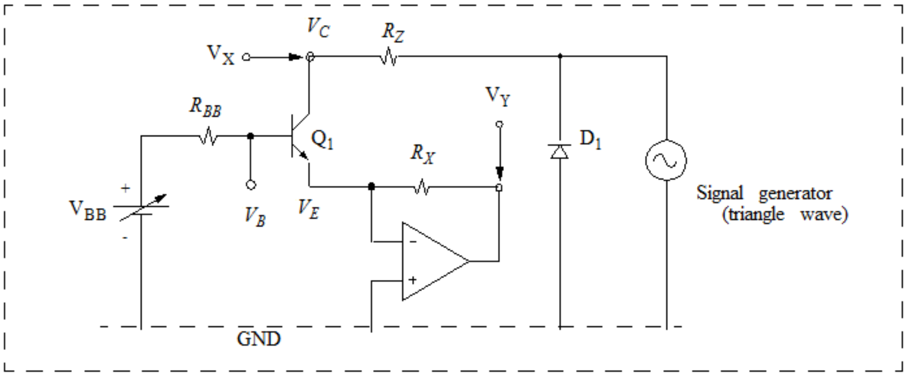


**Figure 4(a)** Test frame for measurement of *npn* BJT characteristics. Oscilloscope CH-1 is wired to node $V_X$ and Oscilloscope CH-2 is wired to node $V_Y$.

The signal generator is set to approximately 8V pk-pk at $f_S$ = 1kHz. Base bias $V_{BB}$ is adjusted to yield transistor forward characteristics [1] at different base current levels as defined by $V_{BB}$ and $R_{BB}$. The resulting trace (Figure 4(b) will look like a bent wire and is consistent with that for a single trace of the 'family of traces' represented by Figure 4(c). The trace is upside down relative to those of Figure 4(c) as a consequence of the inverting configuration required for the current sensing topology. A mild hysteresis also occurs, probably due to recombination in the base. So sweep frequencies were reduced to 50Hz.

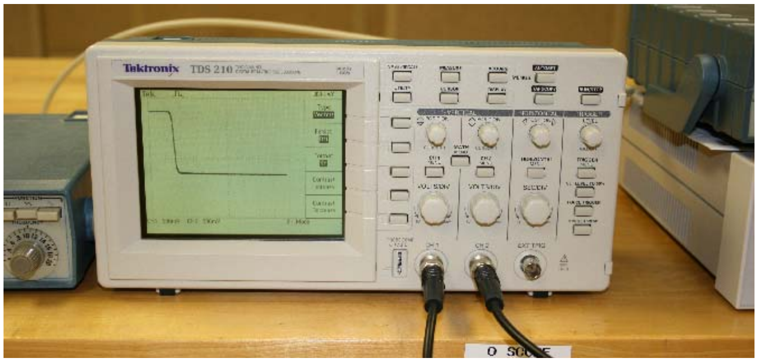


**Figure 4(b).** Photo snapshot of XY output trace courtesy of the test frame of Figure 4(a). Because the current sensing topology inverts the signal, the y-axis corresponding to collector current represented by Figure 4(c) is negative

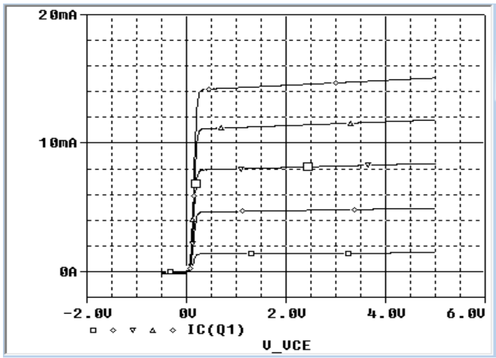


**Figure 4(c).** pSPICE [3] simulation-generated BJT characteristics for comparison to Figure 4(b). Measurements of each Oscope trace are made for determination of [2] (a) forward current gain $\beta_F$ and (b) forward Early voltage $V_{AF}$ (slope parameter for the saturation regime)

**(c) Measurement of CMOS logic circuits characteristics**

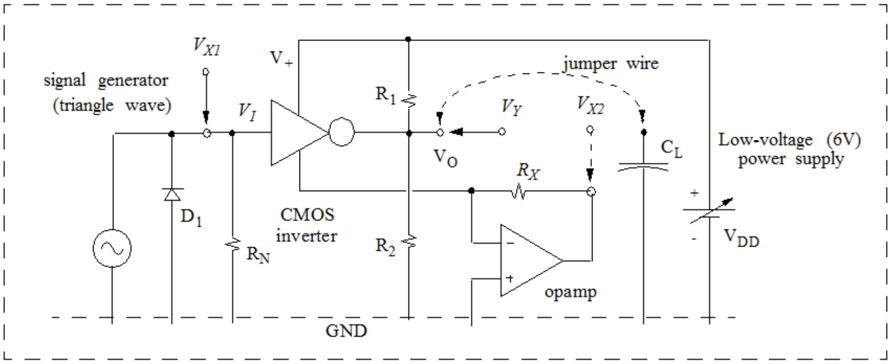


**Figure 5(a)** Test set-up for (1) evaluation of CMOS transfer curve $V_O$ vs $V_I$ and (2) inverter transition current [4]. For transfer characteristics $V_O$ vs $V_I$, node $V_I$ is wired to CH-1 and $V_O$ is wired to CH2- of the oscilloscope (labeled as $V_{X1}$ and $V_Y$, respectively, in the figure) and the Oscope is set to the X-Y mode.

Both transfer characteristics and transition current can be displayed if they are viewed as a time sweep, as shown by Figure 5(b). The transition current profile will be inverted, courtesy of the inverting topology of the current sensing construct. For the figure shown, $V_O$ is wired to CH-2 and $V_{X2}$ is wired to CH-1.

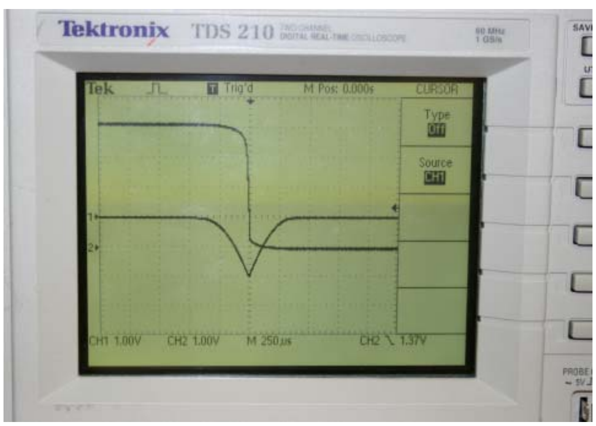


**Figure 5(b).** Photo snapshot of inverter characteristics. The upper trace = CH-2, represents the CMOS transfer curve trace. The lower trace is CH-1 and represents the transition current profile, inverted by the opamp topology. The traces are stabilized by setting the trigger mode to the CH2 falling edge.

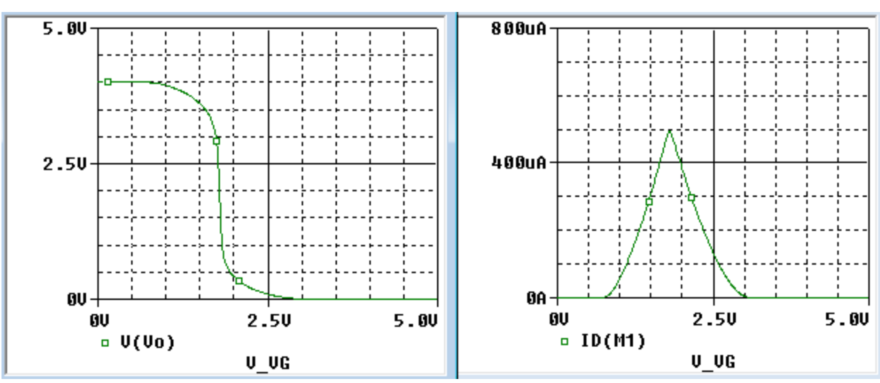


**Figure 5(c).** pSPICE [3] simulation comparisons to the traces of Figure 5(b)

Measurements are made of peak current $I_{MAX}$ and transition current profile width $\Delta V$ with the latter translated from the time scale. The peak of the current profile may also be used to identify the inverter threshold $V_{IT}$ for additional measurements on a CMOS NAND wired as an inverter in each of the three possible equivalent topologies.

## V. SUMMARY

The technique was employed in a series of undergraduate laboratory experiments for introductory electronics and oriented toward both the characterization of semiconductor devices and their use in simple circuit building blocks. The intent was to characterize and compare the conduction properties of devices, most of which were non-linear.

The first laboratory in the set was given to characterization of a general-purpose opamp, inasmuch as the later usage requires use of the opamp both as a current probe and as a means to insert a virtual ground into the measurement string as outlined by Section III. Otherwise, the technique is simple, straightforward and accurate, and lends itself to a reasonably quick and effective extraction of data. If data logging interfaces or access to a backplane were included with the user platform (i.e. the student laptops or netbooks, etc. ) then an import of data directly into a spreadsheet would open the device characterization process to a curve-fitting to models with more parameters of interest, such as those associated with Zener breakdown or those associated with metal-semiconductor junctions.

The emphasis is that the technique as outlined gives a good clean separation of the current measurements and the voltage bias applied to the device and so there are fewer measurement anomalies that need to be considered in the *I-V* analysis. The improved measurement visibility also provides better throughput and allows more options to be explored in the timeframe allocation. The simplicity of the technique is also of benefit to protoboard setup and debugging, which are caveats that must be considered when any appendages are added to a laboratory exercise.

In summary, the technique is clean and simple. It has proven itself in the pedagogical environment. And it has found a niche in different experiment options with minimum insertion overhead. Its simplicity suggests that it should have provenance either in the literature or other resources. But if so, it is relatively obscure and a search did not bring up anything that could be cited, probably because it is more a technique than an exposition and specifically for benefit of the undergraduate laboratory environment.

## REFERENCES

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