A Simple Laboratory Experiment to Measure e/k

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The measurement of fundamental constants is common practice in instructional laboratories. A number of the equipment manufacturers have developed apparatus for such applications, e.g., the determination of *e* by the Millikan oil drop method or the determination of the speed of light with fiber optics. Other experiments determine not a single constant, but a combination of constants, e.g., *e*/*m* by electron beam deflection in a magnetic field or *h*/*e* by the photoelectric effect. About 30 years ago Carl E. Miller and I[1] proposed a method of measuring *e*/*k*, the ratio of the electron charge to Boltzmann's constant, that was reasonably simple but not necessarily inexpensive because it involved the use of a sensitive electrometer. In recent years, however, inexpensive digital multimeters (DMM), many costing less than $30, have found their way into the physics laboratory. The purpose of this paper is to suggest the use of two DMMs, one operating as a voltmeter and the other as an ammeter, in a simple circuit involving a junction transistor and a variable potential source. Even the potential source can be quite simple, a 1.5-V battery and a 1-kΩ potentiometer, as shown in Fig. 1. If available, a variable dc power supply replacing the battery and potentiometer would be more convenient.

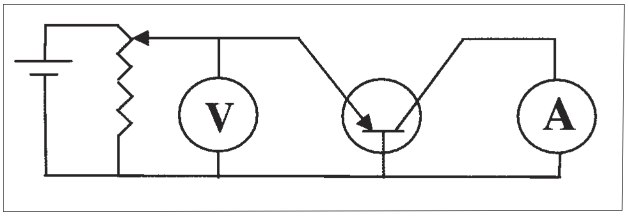

Fig. 1. Experimental arrangement.

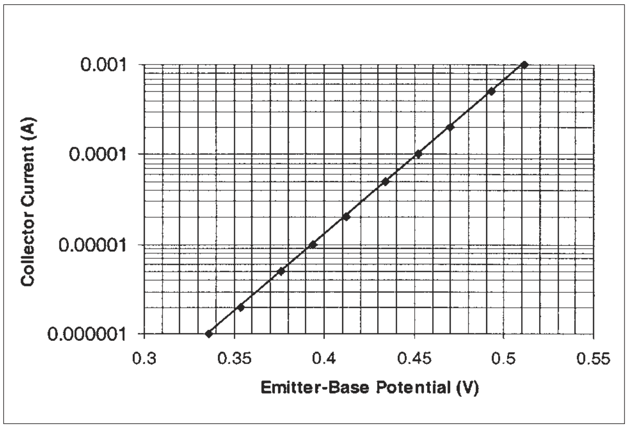

Fig. 2. Collector current vs emitter-base potential for a power pnp transistor.

The various mechanisms that contribute to the current in a transistor are discussed in Ref. 1. Here we will summarize by noting that the collector-base short-circuit current is dominated by the charge carriers that diffuse through the emitter-base junction and into the collector region. The current-potential relation for this diffusion current is given by

$$I_c = I_0 \exp(eV_{EB}/kT), \tag{1}$$

where I_c is the collector current, I_0 is a constant, V_{EB} is the emitter-base potential difference, and T is the Kelvin temperature of the transistor. If we take the logarithm of Eq. (1), we obtain

$$\ln I_c = \ln I_0 + eV_{EB}/kT. \tag{2}$$

Thus, the logarithm of the collector current is a linear function of the emitter-base potential difference,

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Table I. The slope *e/kT* (V^{-1}) for four transistors and three collector current ranges.

Range of collector current	1–10 μ A	1–100 μ A	1–1000 μ A
Small signal pnp	39.11 ± 0.65	39.13 ± 0.20	38.98 ± 0.10
Small signal npn	39.67 ± 0.95	39.48 ± 0.27	39.10 ± 0.10
Power pnp	39.95 ± 0.46	39.79 ± 0.18	39.55 ± 0.11
Power npn	39.95 ± 0.46	39.63 ± 0.25	39.24 ± 0.15

with a slope of e/kT. Knowing the temperature of the transistor allows one to determine the ratio e/k. This temperature would be room temperature provided the current flowing in the transistor is sufficiently small.

The choice of transistor is not critical. We have shown a pnp type in Fig. 1, but an npn type could just as readily be used by reversing the polarity of the potential source. In addition, either a small signal transistor or power transistor can be utilized. But since we want to minimize the temperature rise due to the current flowing in the transistor, a power transistor is probably preferable to the small signal type because of its larger heat capacity. Figure 2 shows the collector current versus emitter-base potential for a pnp power transistor. The collector current varied over the range from 1 μA to 1 mA as the emitter-base potential was varied. The predicted linear relation [Eq. (2)] between $\ln I_c$ and V_{EB} appears justified experimentally. A linear regression analysis of $\ln I_c$ versus V_{EB} yields a value of $39.55 \pm 0.11\ V^{-1}$. The room temperature was 291.5 ± 0.5 K. This yields a value for e/k of $(1.153 \pm 0.004) \times 10^4\ K\,V^{-1}$, as compared to the accepted value of $(1.1604505 \pm 0.0000020) \times 10^4\ K\,V^{-1}$. The error quoted arises from the linear regression analysis and the temperature uncertainty. It does not take into account other factors, e.g., the DMM accuracies, the possible heating of the transistor by the current, or any deviations from the simplified model of electron-hole conduction in a transistor. Note that the current DMM introduces an unavoidable small potential difference so that the requirement to measure the short-circuit collector-base current is not precisely met.

Three other transistors were also used to test this method of determining e/k, namely, a power npn transistor, a small signal pnp transistor, and a small signal npn transistor. They produced similar results. One has to be concerned about the possible temperature rise when current flows through the transistor and whether this problem is worse for small signal transistors. By examining several current ranges with these transistors, one can compare the resulting slopes, e/kT, to see if they depend upon the choice of current range. Table I shows results from these studies. All errors quoted are standard deviations obtained from the linear regression calculations.

Using the accepted value for e/k and our room temperature of 291.5 ± 0.5 K, one finds that the expected value of the slope, e/kT, is $39.81 \pm 0.07\ V^{-1}$. Notice that for each transistor, the larger the current range the smaller the value of the slope e/kT, although the difference is usually within the error range. These results suggest that there may be a temperature effect, that is, a larger current produces some heating, which raises the temperature and lowers the value of e/kT. One would be advised to limit the current to lower levels, but a compromise might be required if we are to avoid the large errors of too small a current range. Notice that if we limit the current range to 1–100 μA, then the slope e/kT for both power transistors is within one standard deviation of the expected value of $39.81 \pm 0.07\ V^{-1}$.

Even though these more subtle aspects merit consideration, they need not be an integral part of the experiment. It is worth noting that this simple experiment yields a value of e/k within 4% of the accepted value for all three collector current ranges tested in four different transistors.

Reference

1. Fred W. Inman and Carl E. Miller, "The measurement of e/k in the introductory physics laboratory," *Am. J. Phys.* **41**, 349 (1973).

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Fred Inman *retired in 1997 after 40 years of teaching, the last of which were at Minnesota State University.*

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