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The Measurement of e/k in the Introductory Physics Laboratory

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The ratio of electronic charge to Boltzmann's constant can be easily determined by measuring the short-circuit collector current versus the emitter-base voltage characteristics of a silicon transistor connected in the common-base mode. The incorporation of this experiment in the introductory physics laboratory is recommended.

INTRODUCTION

The measurement of fundamental constants in both introductory and advanced physics laboratories is a common practice. Fundamental constants that are often determined include the ratio e/m, using a Bainbridge apparatus; h/e from the photoelectric effect; c, using a Michelson rotating mirror apparatus; and e, with a Millikan oil drop apparatus. A fundamental constant that is less frequently measured is Boltzmann's constant, k. The experiment described here provides a simple method for measuring e/k. By combining the results of this measurement with an independent determination of e, one may obtain the value for Boltzmann's constant.

The experiment is based upon the fact that the short-circuit collector current in most commerical silicon transistors operated in the common base mode is an exponential function of the emitter-base voltage, V_{EB}, over a wide range of currents.[1]

$$I_C = I_0 \exp(eV_{EB}/kT). \qquad (1)$$

Therefore, a graph of I_C vs V_{EB} on semi-log graph paper is a straight line with slope e/kT. If the temperature is also measured, e/k is determined. In fact, runs at different temperatures may be made to show the effect of temperature upon the slope of the curve.

The current–voltage characteristics of diodes and transistors have been extensively discussed in the literature.[2] In a pn junction electrical conduction involves several mechanisms including (1) the diffusion current, (2) recombination-generation current in the depletion region, and (3) surface currents. Each of these three components of the total current has a different dependence upon the junction voltage. The theory of the diffusion current was first developed by Shockley[3] and predicts a current proportional to $\exp(eV/kT)$ for forward biased junctions. The recombination-generation current was discussed in detail by Sah, Noyce, and Shockley,[4] and for forward biased junctions this current is proportional to $\exp(eV/2kT)$. The various surface effects produce a current proportional to $\exp(eV/mkT)$, where $m>2$. In a diode all of these currents may be present, and it has been customary to describe the current-voltage characteristics with an empirical relation

$$I = I_0 \exp(eV/mkT) \qquad (2)$$

where m is determined experimentally. Thus, a diode is not a useful device for measuring e/k, since the measurement of the current-voltage characteristic only yields e/mkT and m is not known *a priori.*

For a transistor connected in the common base mode, the collector current is predominantly due to charge carriers that diffuse through the emitter-base junction into the collector region. Thus, the collector current has essentially the same dependence upon the emitter-base voltage as the emitter-base diffusion current, namely,

$$I = I_0 \exp(eV_{EB}/kT). \qquad (3)$$

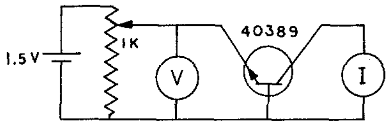

Fig. 1. The circuit schematic used to measure the ratio e/k.

For many silicon transistors this relation has been found to hold to within about 1% over six or more decades of collector current.[1] Therefore, a transistor has obvious advantages over a diode for measuring e/kT.

EXPERIMENTAL DETAILS

A RCA 40389 power transistor was chosen for this experiment because it is readily available, inexpensive ($1.05), and comes with its own heat sink. The transistor was suspended inverted with the heat sink fins immersed in an oil bath. The inner can of an ordinary calorimeter contained the oil and the outer can contained water that was cooled with ice or heated with an electric heating element. The heat sink must not be in electrical contact with the calorimeter cup.

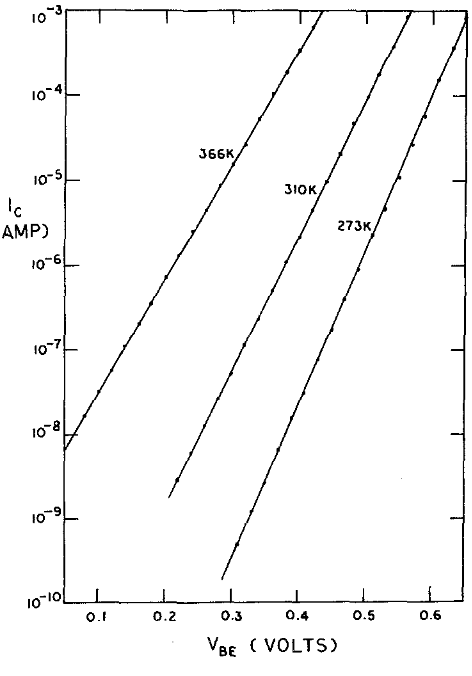

Fig. 2. A semi-logarithmic graph of the experimental data for three different temperatures.

Figure 1 is the circuit used to measure the current-voltage characteristic. The current meter used was a Hewlett-Packard model 425A, but almost any electrometer could be used. The largest current that can be measured with the Hewlett-Packard 425A is 3 mA, so the power dissipated within the transistor was always less than about 1 mW. This was a convenient upper limit in power dissipation because any greater power might produce a significant temperature difference between the oil bath and the semiconductor. The voltmeter used was an RCA model WV–98C Senior VoltOhmist.

Data were taken at three different temperatures. Figure 2 is a graph of these data. Unweighted least squares straight line fits were made to these data and the values of e/kT and e/k are given in Table I.

Table I. Experimental results.

Temperature K	e/kT (Volts)$^{-1}$	e/k C-K/J
273	41.57 ± 0.10	$(1.1354 \pm 0.0029) \times 10^4$
310	37.09 ± 0.14	$(1.1521 \pm 0.0043) \times 10^4$
366	31.25 ± 0.29	$(1.1436 \pm 0.0108) \times 10^4$
Weighted mean of e/k		$(1.1408 \pm 0.0024) \times 10^4$
Accepted value of e/k		$(1.160485 \pm 0.00006) \times 10^4$

The quoted error is the standard deviation obtained from the least squares calculation and does not incorporate explicitly instrument errors. The weighted mean value of e/k is also given in Table I and compared with the accepted value. The difference of 2% between these results is a systematic error consistent with the precision of the RCA WV-98C vacuum tube voltmeter used to measure the emitter base voltage. Since the logarithm of the current was used in the least squares fit, the error introduced by the Hewlett–Packard 425A current meter is negligible when compared with the voltmeter error. The temperature measurement contributes a negligible error, also.

CONCLUSIONS

The experiment may also be performed without using an oil bath. The heat sink maintains the transistor at ambient temperature if the power dissipation is sufficiently low (below 1 mW). This simplifies the experimental arrangement somewhat; however, data is only obtained at ambient temperature. Also, other transistors could be used, but a power transistor is recommended because of its excellent thermal stability. This experiment can be a useful addition to an introductory physics laboratory because it is simple and reasonably accurate (usually as good as the voltmeter used). The measurement of fundamental constants has important pedagogic value, because these constants determine the scale of physical phenomena.

[1] C. T. Sah, IRE Trans. Electron. Devices **ED-9**, 94 (Jan. 1962).

[2] S. M. Sze, *Physics of Semiconductor Devices* (Wiley-Interscience, New York, 1969). This book, in addition to discussing many of these aspects, contains an extensive bibliography.

[3] W. Shockley, Bell Syst. Tech. J. **28**, 435 (1949); also, see almost any solid state physics text for a derivation [e.g., A. J. Dekker, *Solid State Physics* (Prentice-Hall, Englewood Cliffs, N.J., 1957)].

[4] C. T. Sah, R. N. Noyce, and W. Shockley, Proc. IRE **46**, 1076 (1958).

Experiments in Molecular Physics with an Acoustic Interferometer

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An acoustic interferometer provides an inexpensive means for making precise studies of the kinetics of gas molecules. Two experiments are described: (1) Measurement of the vibrational relaxation time of gas molecules and (2) determination of intermolecular (van der Waals) forces in molecules.

Good laboratory experiments which illustrate the kinetic theory of gases are difficult to find. An acoustic interferometer, operating at ultrasonic frequencies, is a versatile instrument for performing several such experiments in the intermediate and advanced laboratories.

Figures 1 and 2 illustrate an interferometer of the Pierce type[1] constructed for the advanced laboratory at St. Olaf College. An X-cut quartz crystal generates nearly-plane ultrasonic waves and also serves as a detector of acoustic standing waves. The reflector is a glass plate carried by a metal piston whose position is measured by a dial gauge. With this apparatus it is possible to measure the velocity of sound to an accuracy of 0.1% or better even at low gas pressures.[2,3]

EXPERIMENT I: MEASUREMENT OF THE VIBRATIONAL RELAXATION TIME OF GAS MOLECULES

The velocity of sound in an ideal gas is given by

$$V^2 = (RT/M)[1+(R/C_v)] \qquad (1)$$

where M is the molecular weight and C_v the molar heat capacity at constant volume. In any gas