Interpretation of α-Values in p–n Junction Transistors

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(Received October 20, 1952)

By the measurement of five parameters in several p-n junction transistors, *viz.*, the conductivities and diffusion lengths of minority carriers in the emitter and base regions and the widths of the base regions, the current amplification factor α of the transistors has been computed from theory. Previous to this investigation two of the parameters associated with the thin p-layer had not been measured. The quantity α also was obtained independently by two alternate methods: (1) by measuring the collector-emitter current characteristic, and (2) by measuring the apparent quantum efficiency of the transistor as a two-electrode photocell with a floating base. The three determined values of α for each sample agree within the experimental error.

INTRODUCTION

The p-n junction transistors studied in this investigation[1] consist of a single crystal of germanium in which normally a thin layer of p-type semiconductor is sandwiched between two n-type end sections. Electrons from one n-type section, the emitter, are injected into the p region where some or most of them diffuse to the boundary between the p layer and the second n section, the collector. With a reverse bias across this second junction, electrons reaching this junction fall down hill into the collector and are registered as collector current.

For this device the current amplification factor α is defined as $-\partial I_c/\partial I_e$ at constant collector voltage. I_c and I_e are collector and emitter currents, respectively. It is apparent physically that α depends on three factors: (1) γ: the fraction of the current carried by electrons, across the emitter junction, (2) β: the fraction of the electrons emitted into the p region which arrive at the collector junction, and (3) α^*: the ratio of change in total current to change in electron current reaching the collector junction.

It has been shown theoretically by Shockley[2] that α^*, β, and γ are simple functions of five parameters characteristic of the semiconducting material. Measurement of these parameters obviously would afford an additional check on the consistency and applicability of the theory. Such has been the purpose of this experimental investigation.

The relations can be expressed as

$$\gamma=\frac{1}{1+(\sigma_b/\sigma_e)(L_b/L_e)\tanh(w/L_b)}\simeq\frac{1}{1+(\sigma_b/\sigma_e)(w/L_e)},$$

$$\beta=\operatorname{sech}(w/L_b)\simeq 1,$$

$$\alpha^*=1 \quad \text{for} \quad \sigma_c\gg\sigma_i,$$

$$\alpha=\gamma\beta\alpha^*,$$

where σ_c = conductivity of collector region, σ_b = conductivity of base layer, σ_e = conductivity of emitter region, σ_i = conductivity of intrinsic germanium, L_b = diffusion length for minority carriers in base layer, L_e = diffusion length for minority carriers in emitter region, and w = width of base layer. The approximations are valid for $w\ll L_b$.

When the transistor is used as a phototransistor, the apparent quantum efficiency (Q.E.) is related to α uniquely by the same theory.[2]

$$\alpha=(\text{Q.E.}-1)/\text{Q.E.}$$

Q.E. will be defined later in the paper.

Thus, we have been able to measure α for five n-p-n and one p-n-p transistors by three independent experimental methods. 1. Measurement according to the definition: $\alpha=(\partial I_c/\partial I_e)_{V_c}$. 2. Calculation of α from measured values of the five parameters—w, L_e, L_b, σ_e, σ_b. 3. Calculation of α from measured Q.E.

For all six samples, the three determinations of α agree within the experimental errors.

EXPERIMENTAL PROCEDURE

A. Specimens

All the specimens used in these experiments were slabs cut from various single crystals of germanium.[3] They varied in thickness from 0.028 in. to 0.051 in. and were approximately one-half inch in width. The crystals were grown with a base layer width of at least 0.004 in. so that L_b could be measured.

B. Direct Measurement of α

This value of α was determined by taking the slope of the plot of I_c *vs* I_e at constant V_c. As α is insensitive to V_c, $V_c=3$ volts was used since it was convenient.

C. Calculation of α from Measured Values of the Five Parameters

1. σ_e was measured using a four-point probe method (Fig. 1). The general formula[4] for this method is

[1] All the samples had four terminals (two terminals to the base region) and the dimensions of the samples were chosen to be large in comparison with the dimensions of production transistors. However, these samples can be and have been operated as three terminal devices in the manner of conventional n-p-n transistors (the two base region contacts tied together).

[2] Shockley, Sparks, and Teal, Phys. Rev. **83**, 151 (1951).

[3] Teal, Sparks, and Buehler, Phys. Rev. **81**, 637 (1951).

[4] See Appendix.

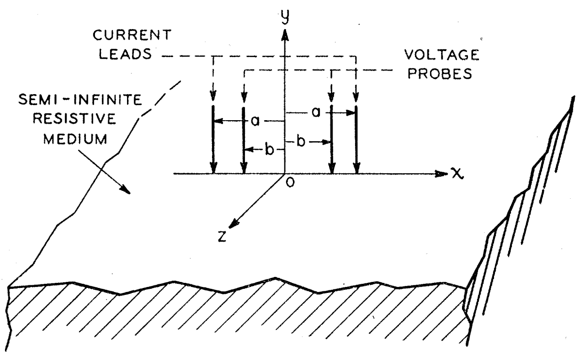

FIG. 1. Four-point probe resistivity measuring device.

$\sigma=[2b/\pi(a^2-b^2)](I/V)$, where a and b are distances shown in Fig. 1, I is the current flowing in the current probes, and V is the voltage across the potential probes. In this investigation, $a=3b=0.19$ cm; therefore $\sigma_e=1.25I/V$. The above relation holds for samples whose dimensions are large compared to 2a.

2. σ_b and w were measured by potential probes. Two contacts were made to the base layer of an *n-p-n* junction transistor (Fig. 2), and the two junctions were biased in the reverse direction. This resulted in small reverse currents flowing across the junctions. The principal current flowed in the base layer between the two contacts. A voltage probe connected to a potentiometer was drawn across the junctions in the x direction for various values of y. A typical set of plots of these probe voltages is shown in Fig. 3. The parameter w is determined directly from these plots and σ_b from

$$\sigma_b=(I/tw)(\Delta y/\Delta V),$$

where I=current flowing in region of base layer, t=thickness of slab, w=width of base layer, Δy=distance between two probes in the x direction, and ΔV=voltage difference in base layer between two probes.

3. L_e and L_b were obtained from measurements of the distance variation of the photocurrent produced by scanning the specimen with a small spot of "chopped" light, in a direction normal to the junctions. The light spot was 2–3 mils in diameter, the frequency of chopping 90 cps, the light and dark intervals of equal duration, and the biasing voltage sufficient to saturate the collector current. In these measurements the specimen was biased as in Fig. 4(a). The 90-cycle component of current was measured by means of the ac voltage it generated across a series resistance small in comparison

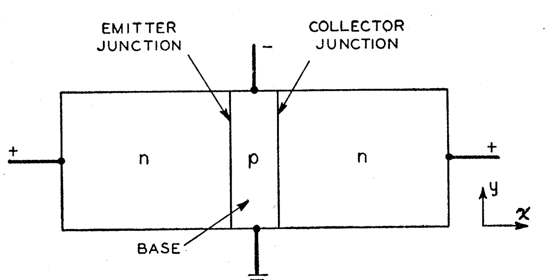

FIG. 2. Electrical polarities for measuring base layer conductivity in *n-p-n* junction transistor.

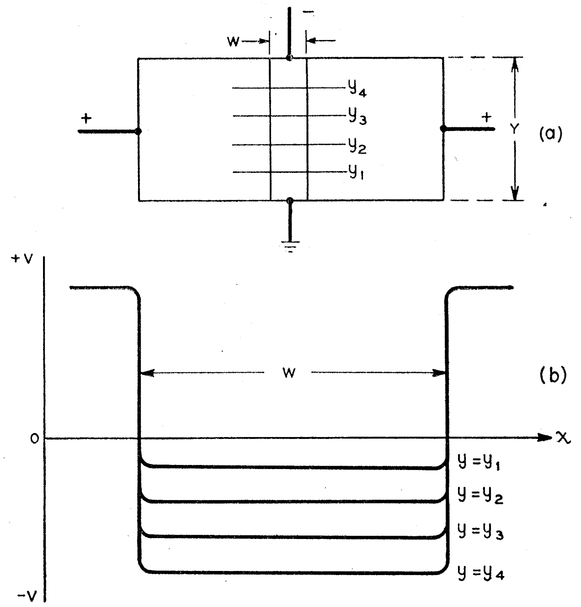

FIG. 3. Probe plots for determining base layer conductivity. (a) Position of probe lines on the crystal. (b) Potential *vs* position for probes.

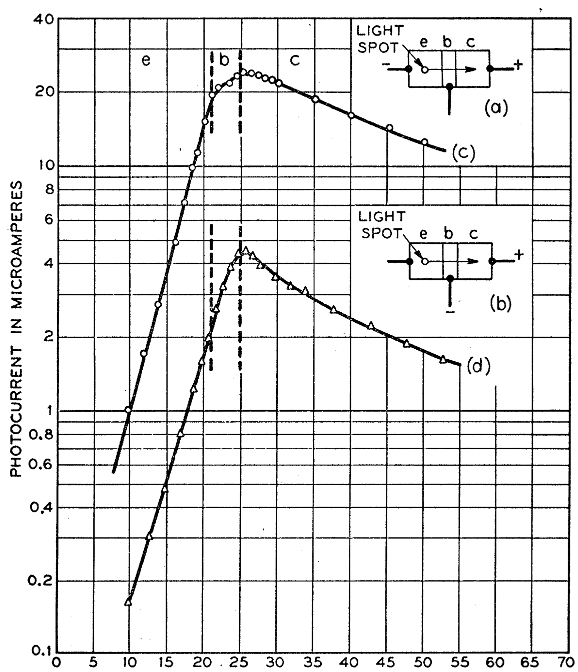

FIG. 4. Diffusion length determinations. (a) Transistor biased for phototransistor operation. (b) One junction biased in reverse for unit quantum efficiency. (c) Photocurrent when transistor is biased as a phototransistor. (d) Photocurrent when one junction is biased in reverse.

TABLE I. Tabulation of experimental data and calculated results.

	1	2	3	4	5	6	7	8	9	10	11	12
Specimen	Type	σ_e mho/cm	σ_b mho/cm	L_e microns	L_b microns	w microns	Calc. γ	Calc. β	Q.E.	Calc. α	Direct measurement α	Q.E. α
16	*n-p-n*	0.098	0.43	216	1020	210	0.19	0.98	1.14	0.19	0.22	0.12
17A	*n-p-n*	2.8	0.50	97	452	103	0.84	0.97	5.4	0.81	0.81	0.82
19A	*n-p-n*	2.6	0.32	266	710	200	0.92	0.96	10.0	0.88	0.79	0.90
19B	*n-p-n*	2.6	0.35	187	687	110	0.93	0.98	11.1	0.91	0.90	0.91
25A	*n-p-n*	15.1	0.44	45	495	600	0.72	0.55	1.68	0.40	0.40	0.40
43	*p-n-p*	29.5	4.9	130	58	161	0.93	0.25	1.27	0.23	0.25	0.21

with the resistance of the collector junction, which was biased in reverse. Under these conditions characteristics such as Fig. 4(c) were obtained. Since the response falls off exponentially from the emitter junction in the emitter region, in agreement with diffusion theory, L_e is determined as that distance which reduces the photoresponse to $1/e$ of its original value.[5] Similarly L_b is determined from the photoresponse data in the base region. However, in this region, it can be shown that L_b must be determined from a more complicated function of L_e, w, and the photoresponse *vs* distance curve, than in the emitter region.

D. Determination of α from the Apparent Quantum Efficiency

The theory of the operation of a *p-n* junction phototransistor using a *p-n* hook collector is discussed in reference 2. The apparent quantum efficiency or amplification factor is defined as the ratio of the peak photocurrent when the light spot falls on the collector junction with the transistor biased as a phototransistor [Fig. 4(a)] to the photocurrent obtained when the same light spot falls on the collector junction biased as in Fig. 4(b). The latter is best obtained by scanning both junctions as in Fig. 4(b). It has been shown[6] that when the light spot is small compared to the diffusion length, the photocurrent with the spot at a *p-n* junction corresponds approximately to unit quantum yield for the absorbed quanta. Therefore, the apparent quantum efficiency is a measure of the amplification factor of the *p-n* junction phototransistor.

TABLE II. Tabulation of probable errors in measured quantities.

Quantity	Probable error percent
σ_e	5
σ_b	2
L_e	10
L_b	20
w	2
Direct measurement α	2
Q.E.	10

EXPERIMENTAL RESULTS AND DISCUSSION

The dependence of α upon σ_e, σ_b, L_e, L_b, and w found in the experiments described above is summarized in Table I. In Table II, there is a listing of the probable errors associated with the measured quantities. Previously reported results[2] indicate that the current voltage relationships are in agreement with theory. The results of these experiments demonstrate that the parameter α can be deduced from measured properties of the structure. The modified experimental structures are in every way similar to an actual transistor structure except in the width of the sample. On the basis of these facts, there can be little doubt as to the soundness of the present theory of the functioning of junction transistors.

We are indebted to W. Shockley, who proposed this investigation, for his advice and support, to M. Sparks for supplying the crystals and suggesting experimental techniques, and to R. Mikulyak who helped in the preparation of the experimental samples.

APPENDIX

Theory of 4-Point Probe Resistivity Measuring Device[7]

Consider a semi-infinite homogeneous resistive medium (Fig. 1) with a pair of current probes at $x=\pm a$ and a pair of potential probes at $x=\pm b$. The potential at any point r due to the two current sources is

$$V(r)=V(a)+\frac{I}{2\pi\sigma|a-r|}+V(-a)-\frac{I}{2\pi\sigma|-a-r|}.$$

Therefore

$$V=V(b)-V(-b)=\frac{I}{\pi\sigma}\left[\frac{1}{a-b}-\frac{1}{a+b}\right]=\frac{2b}{a^2-b^2}\frac{1}{\pi\sigma},$$

or

$$\rho=\frac{1}{\sigma}=\frac{\pi(a^2-b^2)}{2b}\frac{V}{I}.$$

[5] F. S. Goucher, Phys. Rev. 81, 475 (1951).
[6] F. S. Goucher, Phys. Rev. 81, 637 (1951).

[7] For a more general discussion see L. B. Valdes, to be published in the near future.