THE UNIVERSITY OF MICHIGAN

INDUSTRY PROGRAM OF THE COLLEGE OF ENGINEERING

DIODE AND TRANSISTOR TYPE EFFECTS WITH IONS

Robert L. Hess
Associate Professor of Engineering Mechanics
The University of Michigan

Hoshang Patel
Graduate Student in the Department of Chemical and Metallurgical Engineering
The University of Michigan

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PREFACE

We consider this paper to be rather unusual in that it describes, apparently for the first time, a rectifying and amplifying device using ion movement in a gel matrix.

The paper makes no suggestion concerning possible application of this "ionic transistor", but since the materials are commonly available, it becomes apparent that this device can be easily assembled for the purpose of demonstrating transistor action. In fact, the author suggests that a student could construct and test one of these "ionic transistors" in a 2-hour laboratory period.

We expect that further investigations may lead to the development of a number of practical applications of the principles described in this paper.

R. E. Carroll
Industry Program
College of Engineering

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I. SUMMARY

Experiments were performed showing rectification and amplification effects with ionic devices. Solutions of ionic salts in gel form were used to build PN type diodes and PNP and NPN type transistors. The ions interacting were H^+ and OH^-, which behaved similarly to holes and electrons in semiconductors. The effects of changes in ionic concentration and the length of junctions were investigated. The frequency response of the transistor type junctions was measured.

Further investigation along theoretical and experimental lines is recommended, especially with regard to establishing transistor type effects in glass.

II. INTRODUCTION

The development of semiconductor physics has produced several valuable devices in recent years. Two of the more important ones are the transistor and the junction diode. The theory of semiconductor devices utilizes the concepts of electrons and holes (ref. 4). While the physical existence of free electrons is established, the physical existence of a hole away from the nucleus is not claimed. However the hole is an invaluable concept in explaining the working of semiconductor devices. A parallel to the conduction of current by holes and electrons is the conduction of current by positive and negative ions.

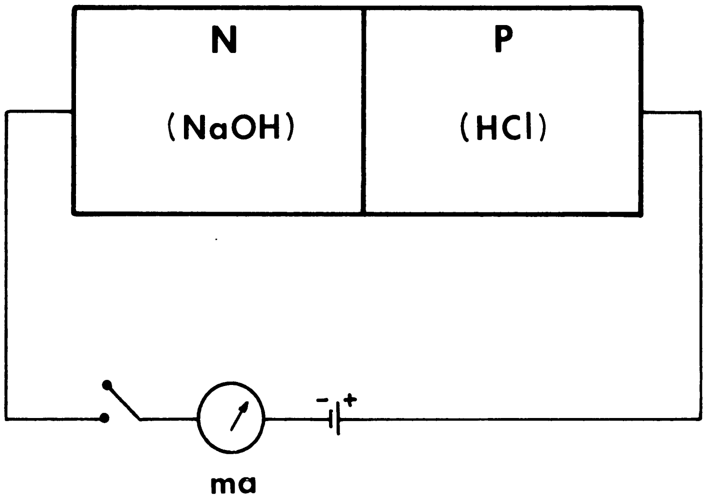
The goal of this study was to duplicate experimentally the junction diode and transistor effects with devices using positive and negative ions. A literature search revealed no previous work along these lines.

III. SEMICONDUCTOR DEVICES AND THEIR IONIC PARALLELS

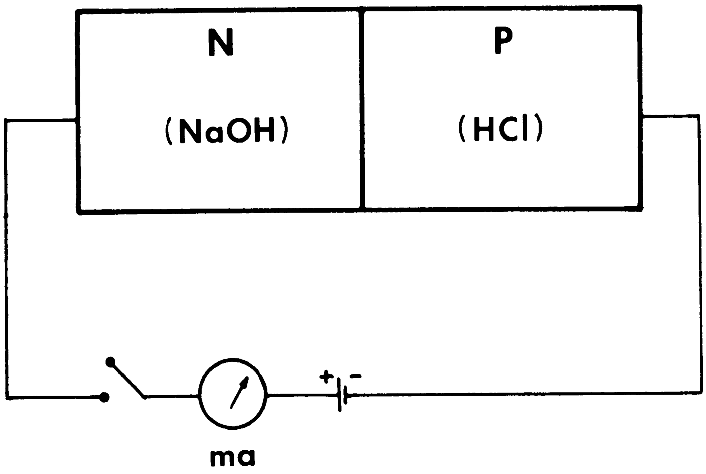
An electron, when in the sphere of influence of the nucleus, has certain possible, discrete values of energy, or energy levels, which are integer multiples of hf, f being a frequency associated with the electron and h, Planck's constant. No intermediate values of energy are permitted. Conducting bands are the higher energy levels, while valence bands are the lower energy levels. Conduction of electronic current occurs when sufficient valence electrons have jumped to the conduction band. In true conductors there is no forbidden zone between the valence and conduction bands. Insulators have an extremely large forbidden zone and therefore conduct very poorly. Materials with a small forbidden zone (of the order of one electron volt) are known as semiconductors, e.g., germanium and silicon.

Germanium has a crystal lattice of quadrivalent atoms held by covalent bonds. When a pentavalent impurity, such as arsenic, is introduced into the structure, it uses four electrons for covalent bonds with the surrounding germanium. There is one electron left over which is unbound and enters the conduction band as a free electron. Therefore such a material is called a donor or an N type. If a trivalent impurity, such as indium, is introduced into the germanium lattice, the indium forms covalent bonds from three of its own electrons, and in addition robs an adjacent covalent bond of its electron. The redistribution of quantum states of the electrons in the system when an electron has been removed from a valence bond is conveniently described in terms of a positive hole. When so regarded, the hole has electron mass, a unit positive charge, velocity and energy. A material with an excess of holes is known as an acceptor or a P type.

Figure 1 illustrates a P-N junction diode. If forward bias is applied as in Figure 1a, electrons of the N section will move into the P section, while



1a. Forward Bias



1b. Reverse Bias

Figure 1. Junction Diode

the holes in the P section will move into the N section. The velocity of electrons is much higher than that of holes. Therefore a net flow of current is established. If reverse bias is applied, as in Figure 1b, both electrons and holes move away from the junction and the current flow is very low. This effect is known as rectification.

To parallel the P-N junction with ions, ~~it~~ was decided to use the H^+ ion for the hole and the OH^- ion for the electron. Here both the positive and negative particles have physical existence. One complication in using solutions of ions is that both positive and negative ions have mobility. In the germanium diode the nuclei are fixed. The method used was to pair a fast ion with a slow ion. Thus the net effect would be as if the fast ion were the electron (or hole) and the slow ion the nucleus. The pairs used were H^+ (fast) and Cl^- (slow) for the P section and Na^+ (slow) and OH^- (fast) for the N section. The relative velocities of these ions are shown by the values of the limiting ionic conductances at 25°C:

Ion	mhos per cm
H^+	349.8
Cl^-	76.34
Na^+	50.11
OH^-	197.6

In order to form stable boundaries, the solutions were made into gels with agar-agar.

Figure 2 illustrates an NPN transistor. The left section is known as the emitter and the right as the collector. The center section is known as the base. The collector circuit is connected with reverse bias and so there is little current through it if the base is wide. The emitter circuit is forward biased and there is current flow between the emitter and base. When the base is "thin" the electrons moving from the emitter to the base go right through it and into the collector region. Thus there is current amplification.

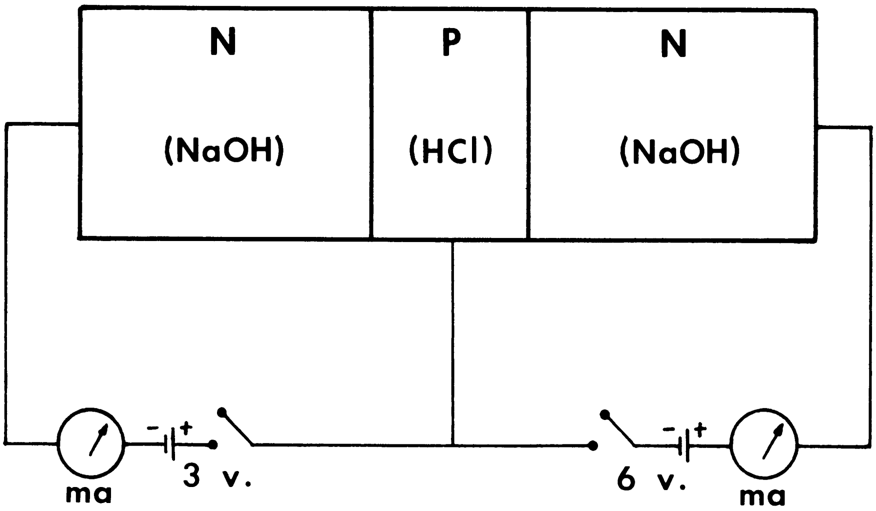


Figure 2. NPN Junction Transistor

Figure 3 shows a PNP transistor. Here again the emitter circuit is forward biased and the collector circuit is reverse biased. When the base is thin, holes from the emitter circuit go right through the base to the collector circuit with resulting current amplification.

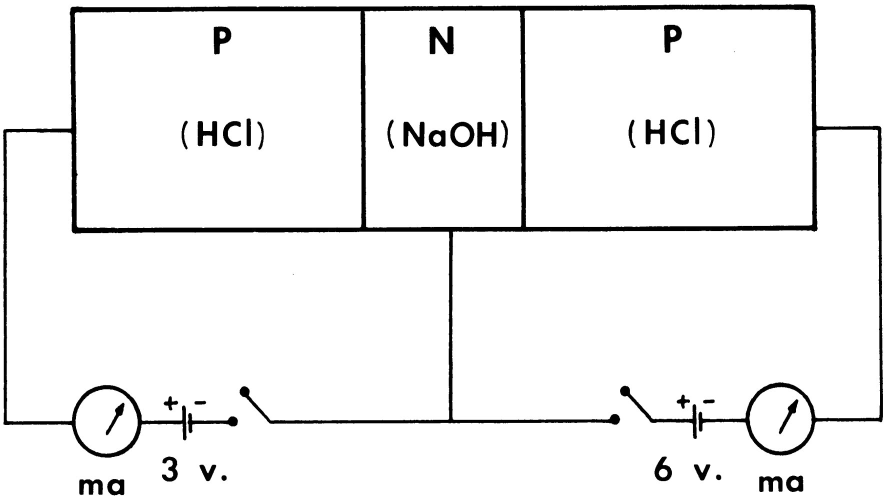


Figure 3. PNP Junction Transistor

The ratio of the current in the collector to the current in the emitter circuit is the current gain. The ratio of the resistance of the collector to the emitter is the resistance gain. The voltage gain is the product of the resistance and current gains. The power gain is the product of the current and voltage gains.

For the ionic parallel, as in the case of the junction diode, the P material was a gel containing HCl and the N material a gel containing NaOH. In the NPN junction OH^- ions jump from the emitter to the collector circuit. In the PNP junction H^+ ions jump from the emitter circuit to the collector circuit. An important difference between the electronic and the ionic device is that while in the electronic, the electron moves faster than the hole, in the ionic the H^+ moves faster than the OH^-. As a result while the electronic device shows voltage gains of the order of a thousand times the current gains, the ionic device has current and voltage gains of the same order of magnitude.

IV. EXPERIMENTAL RESULTS

(The experimental data are given in section VII.)

The optimum concentration of the gel was found to be 3 gm agar-agar dissolved in 100 ml of boiling water. When allowed to cool the mixture forms a firm gel which retains its shape well. For the P type gel 0.5 ml of concentrated (28%) hydrochloric acid was added. For the N type 2 ml of 1 N sodium hydroxide were added. For comparison another set of experiments with 1 ml concentrated hydrochloric acid and the same concentration of sodium hydroxide were performed.

For the junction diode the ratio of the forward resistance to the reverse resistance was always less than one. This shows that rectification was taking place. Figure 4 plots the resistance ratio as a function of length of

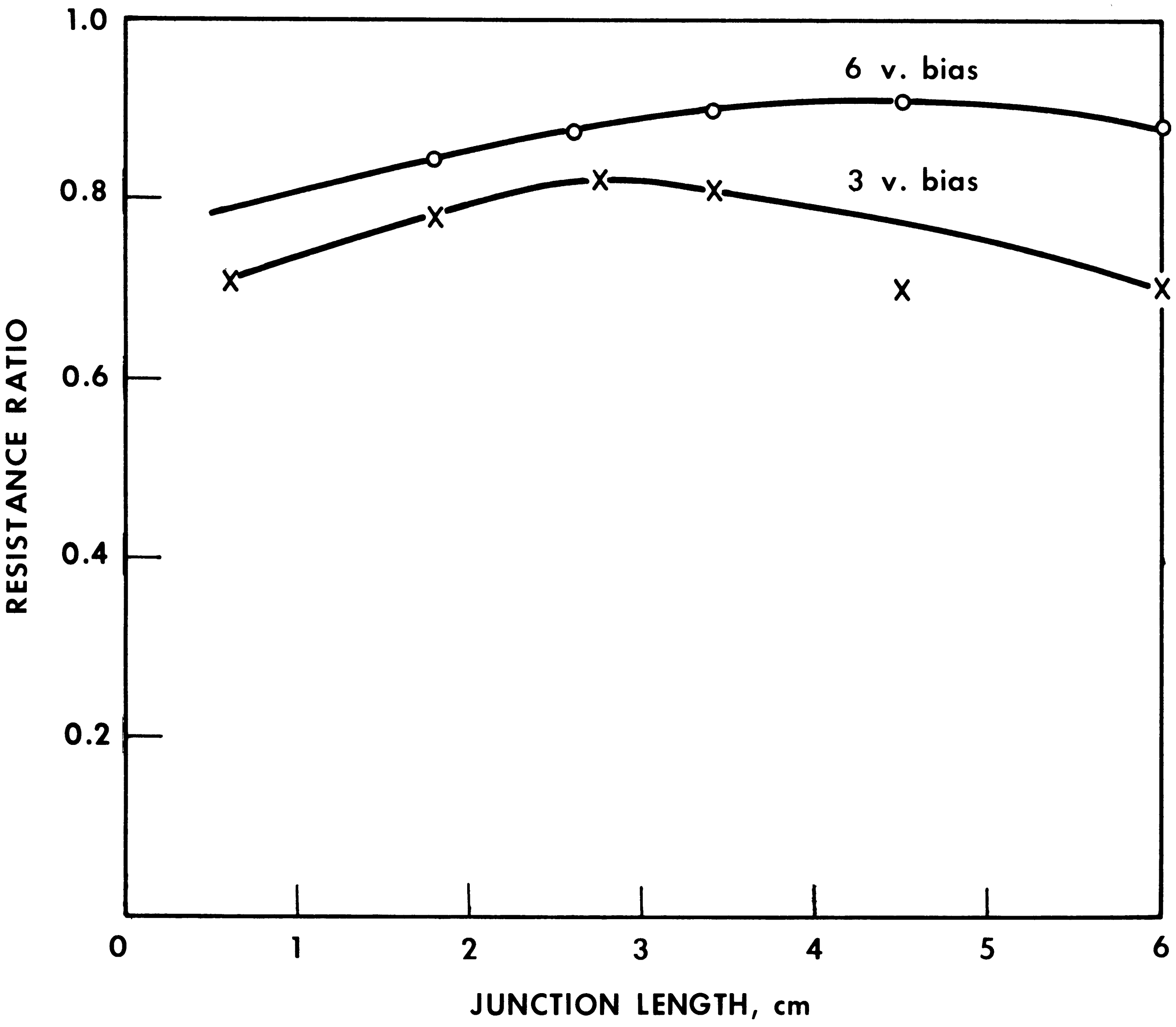


Figure 4

<u>Junction</u> <u>Diode</u>

Resistance ratio (forward bias/reverse bias)
as a function of junction length

the junction, for a six volt and a three volt bias. As expected the ratio is independent of length; the variations are within experimental error. The ratio decreases, that is, the rectification effect increases with lower applied voltage.

The transistor type junctions are shown in Figures 5, 6, 7 and 8 for the PNP and NPN types at low and high HCl concentrations. The current and voltage gains are plotted against the length of the base. The current and voltage gains show maxima between 1-2 cm base length. The effect of increasing the acid concentration is to raise the voltage gain of the PNP and lower the voltage gain of the NPN junction. This is to be expected since in the PNP junction higher H^+ concentration means more emitter H^+ ions can jump across the base to the collector section. More H^+ ions in the NPN junction means that more OH^- ions will be absorbed as they try to cross the base section from the emitter to the collector.

Figures 9 and 10 show the frequency response of the PNP and the NPN junctions. An alternating current signal was generated in the emitter circuit and the resulting voltage in the collector circuit was measured. Maxima are exhibited between 5000-10,000 cycles per second. The curve then drops off rapidly with increasing frequency. The low frequency end of the curve flattens out to a direct current value. As the a.c. bias voltage approaches the d.c. bias value the curves are closer together. That is, an increase in the a.c. signal has a lesser effect when nearer the d.c. bias value. This effect is also observed with electronic transistors.

V. AREAS OF FURTHER STUDY

In this report no attempt is made at a mathematical theory to explain the data. The mathematical analysis is more difficult with the ionic devices

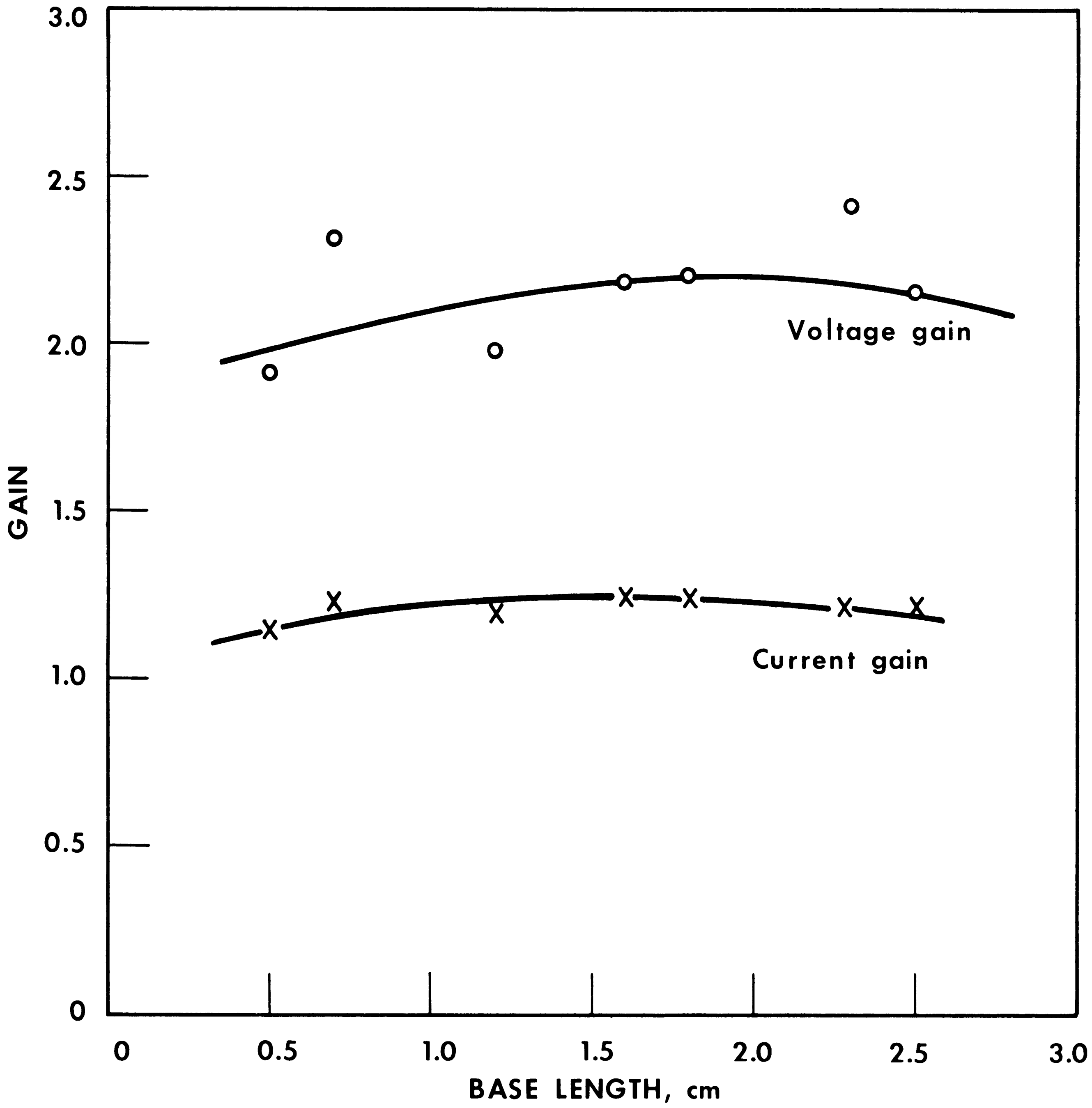


Figure 5

PNP Junction (low HCl)

Gain as a Function of Base Length.

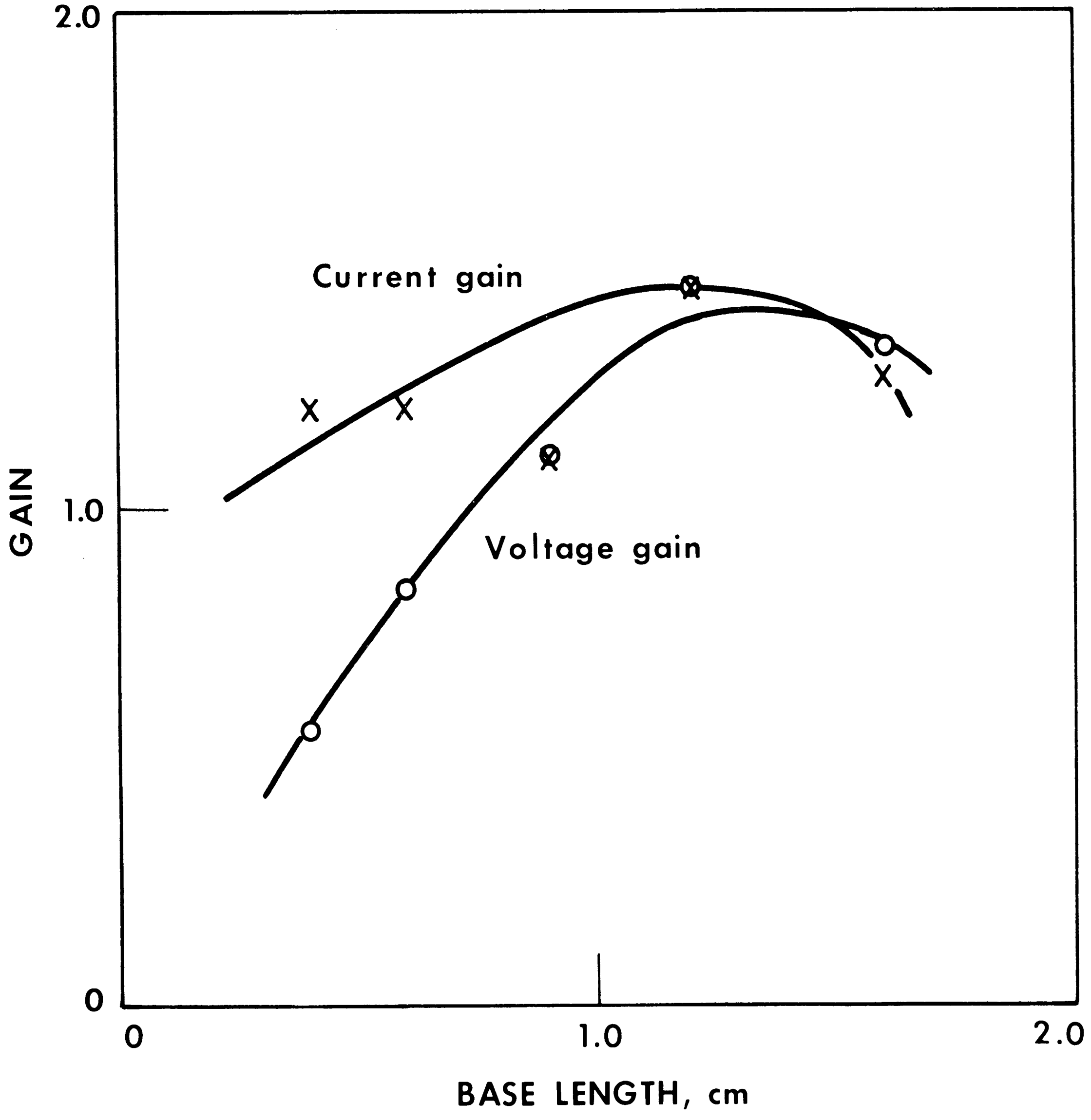


Figure 6

<u>NPN</u> <u>Junction</u> (Low HCl)

Gain as a Function of Base Length

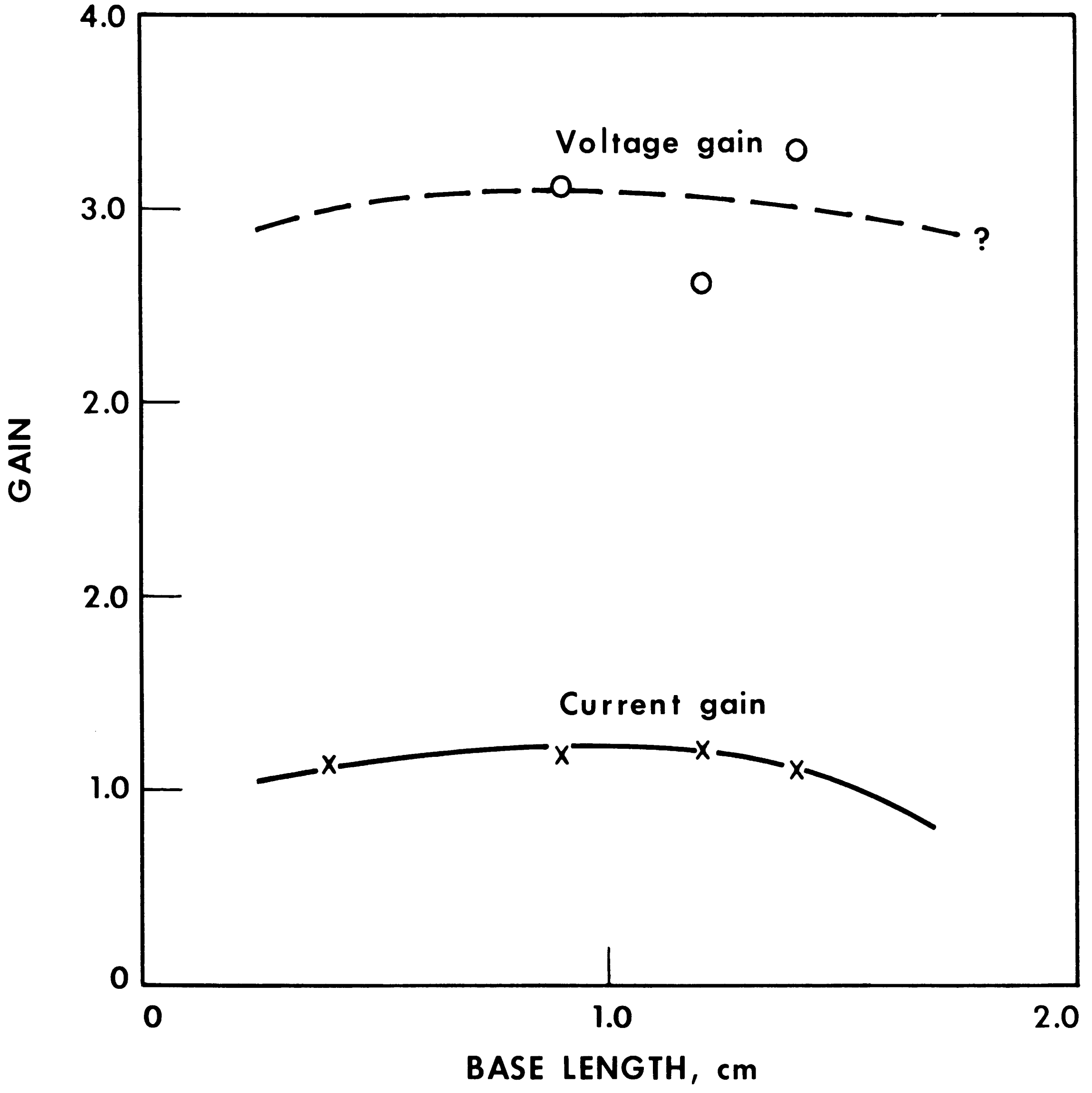


Figure 7

<u>PNP</u> <u>Junction</u> (High HCl)

Gain as a Function of Base Length

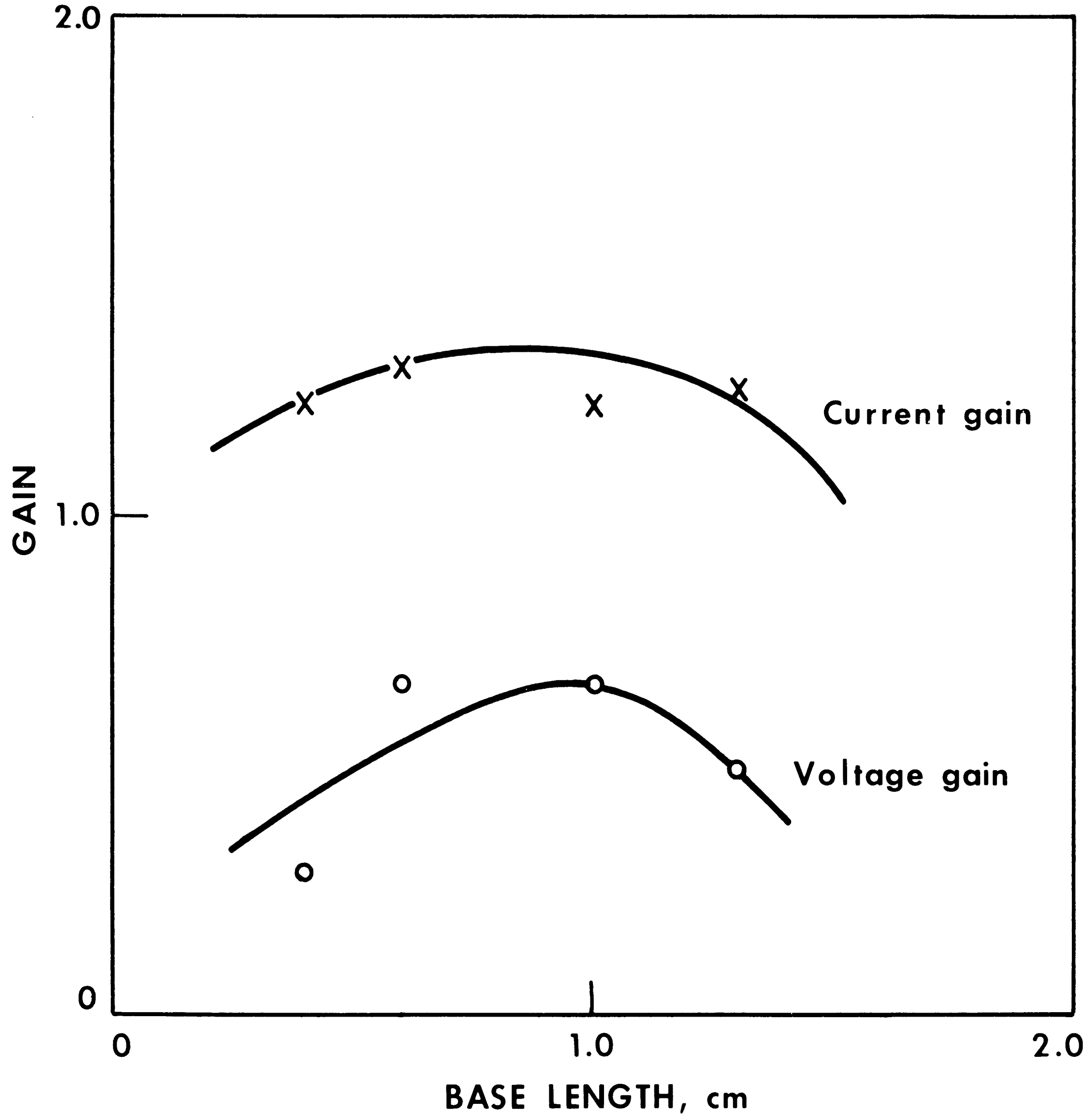


Figure 8

NPN Junction (high HCl)

Gain as a Function of Base Length.

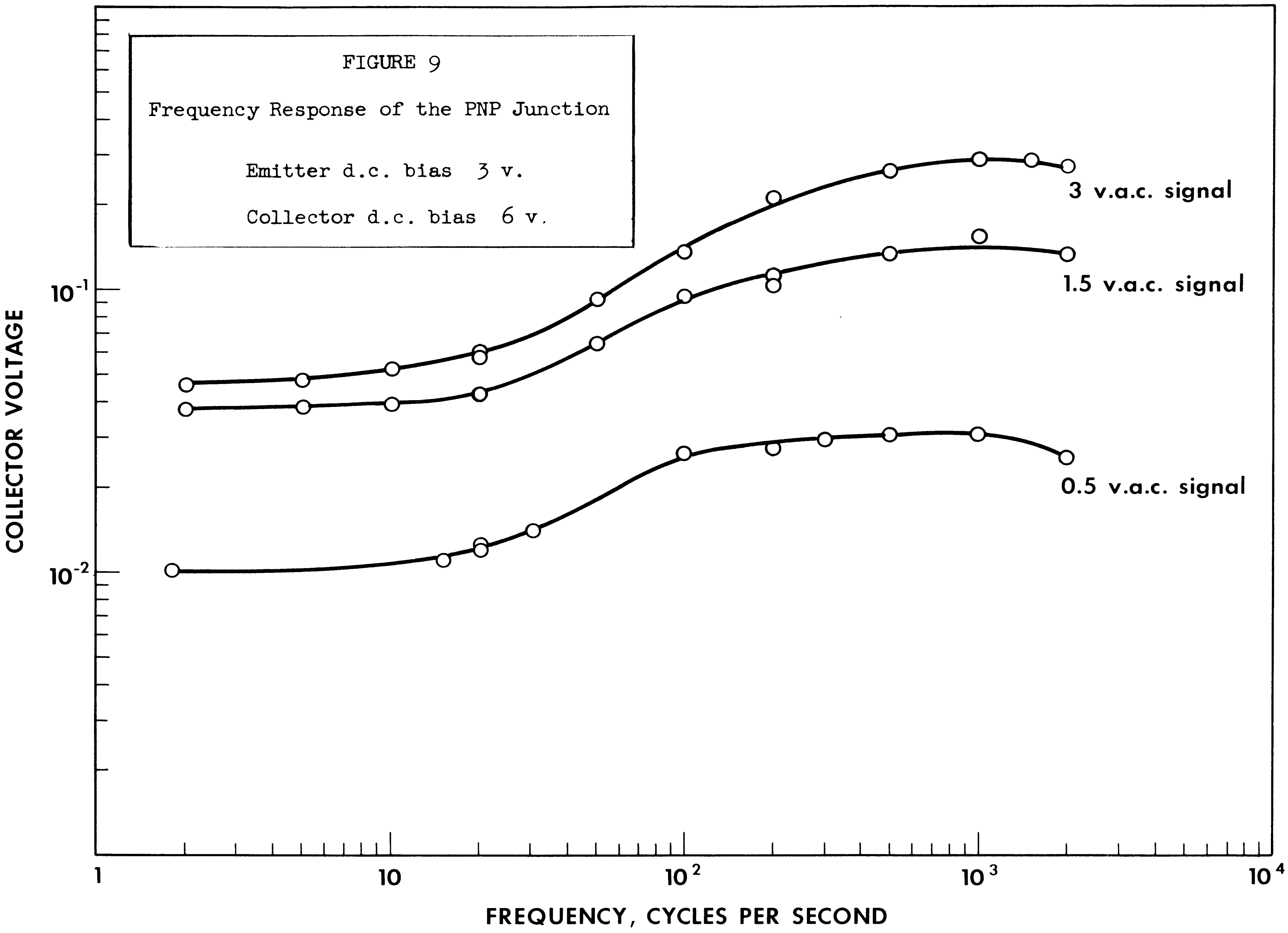


FIGURE 9

Frequency Response of the PNP Junction

Emitter d.c. bias 3 v.

Collector d.c. bias 6 v.

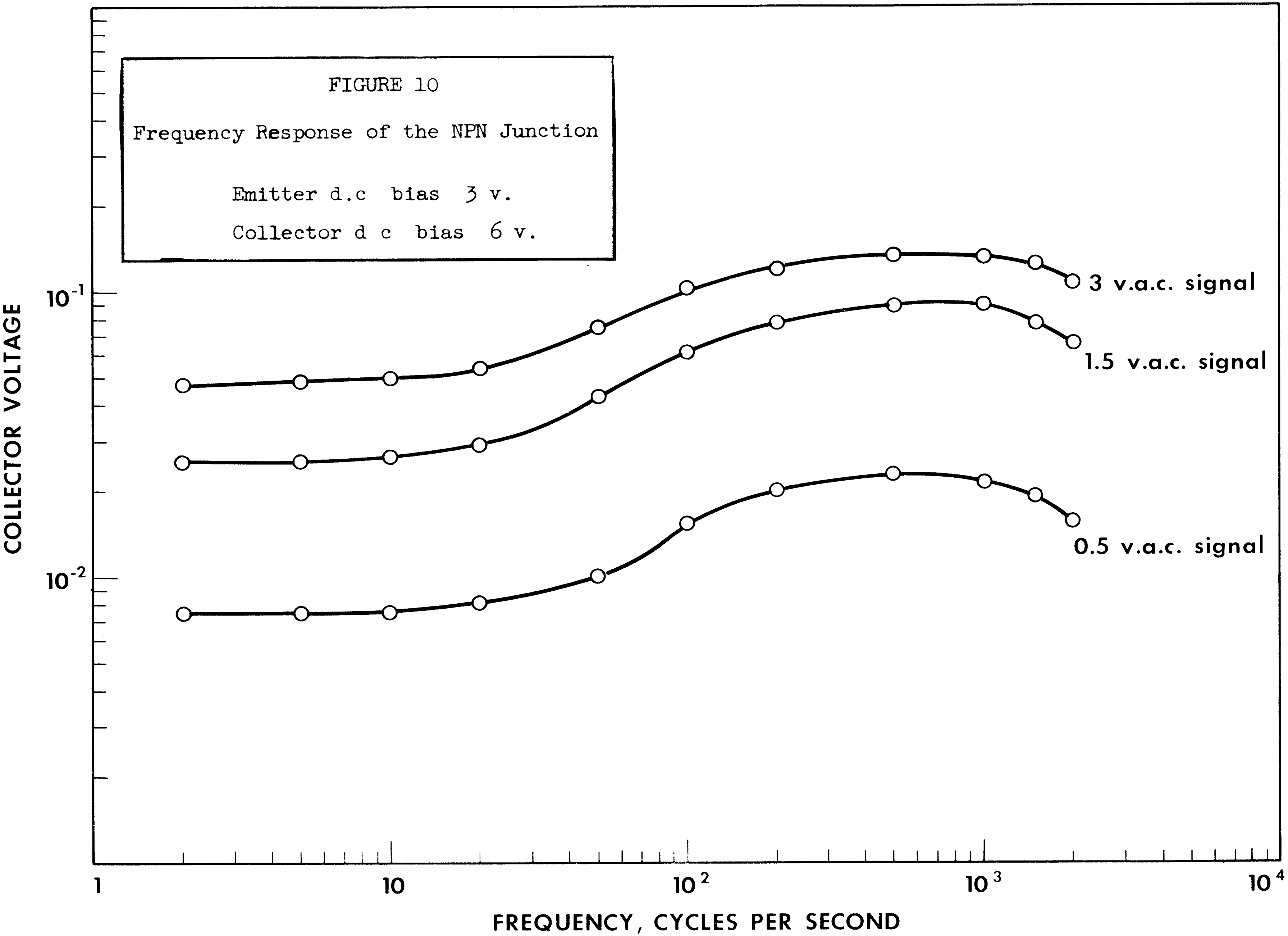


FIGURE 10

Frequency Response of the NPN Junction

Emitter d.c bias 3 v.

Collector d c bias 6 v.

since they use four types of ions as compared to only the electron and the hole. However, it should be possible to set up and solve, analytically or numerically, a differential equation describing the basic rate process occurring.

Further work in measurement of transistor type ionic devices with gels containing different ions should also throw more light on the phenomenon, and perhaps check the theoretical work.

This study indicates the possibility of showing transistor type ionic effects in glass. Morey (ref. 3) reports a number of studies by different investigators showing the conductance of Na^+ ions in glass. If the conductance of negative ions is also possible, then there is a strong probability of the existence of transistor type ionic effects. Such a glass junction would last for a long time and may prove to be more than a laboratory curiosity. Work along this line should give some very promising results.

VI. CONCLUSIONS

1) It has been shown that effects between positive and negative ions parallel effects between holes and electrons.

    a) Rectifying action was observed in a PN type of diode junction where the interaction was mainly between the H^+ and OH^- ions in a gel.

    b) Transistor type of amplifying action with PNP and NPN type junctions was observed with the same ions.

2) The effect of the length of the junction on the rectification or amplification was measured.

3) The effect of ionic concentration change on the PNP and the NPN junctions was measured.

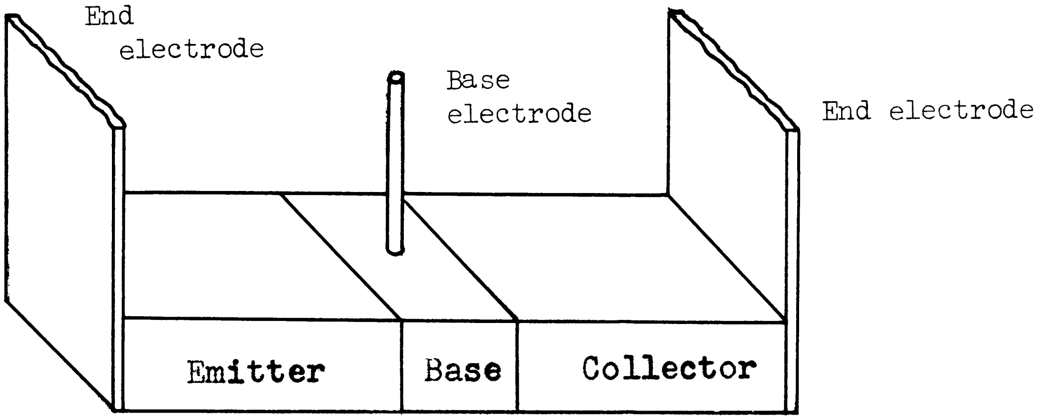
4) The frequency response of the PNP and the NPN junctions was measured.

5) Further investigation has been suggested:

a) along theoretical lines.

b) on the gel medium with changes in the ions.

c) on transistor type ionic effects in glass.



End electrodes : 1/32 in. thick, 1 in. wide copper plate.

Base electrode : # 16 gage copper wire.

Electrodes are supported by "flexaframe" lattice which allows adjustment in all directions.

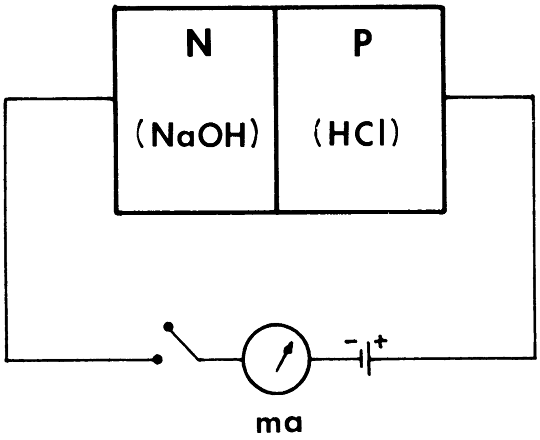
Baseboard : 1 ft square plywood, 1/2 in. thick.

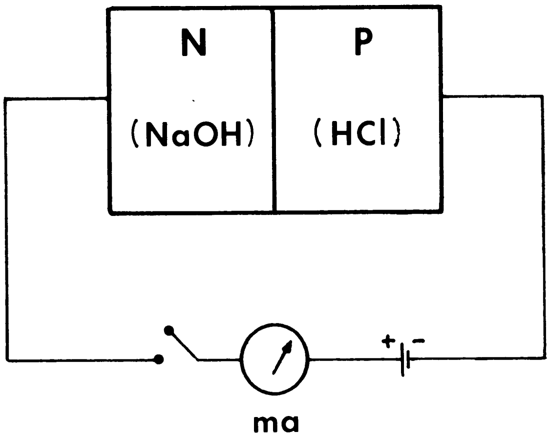
Figure 11

<u>Details of Electrodes</u>

VII. EXPERIMENTAL DATA

Experiment No. 1 Junction Diode (low HCL)*





Junction 2.2 cm wide, 1 cm thick

	6 volt bias		3 volt bias	
Junction length, cm	Forward bias current, ma	Reverse bias current, ma	Forward bias current, ma	Reverse bias current, ma
6.0	7.2	8.2	3.5	5.0
4.5	8.0	8.8	3.5	5.0
3.4	11.0	12.2	3.8	4.7
2.6	12.7	14.5	4.7	5.7
1.8	16.7	19.8	6.4	8.2
0.6	out of range		11.2	15.8

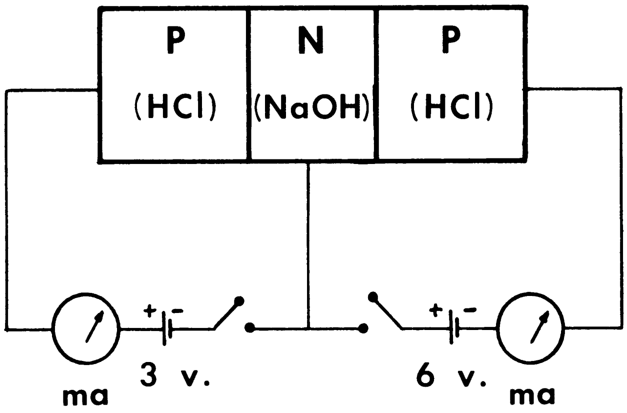
*Note: Makeup of gel is 3 gm agar-agar dissolved in 100 ml hot water.

NaOH gel contains 2 ml 1 N NaOH

Low HCL gel contains 0.5 ml concentrated (28%) HCL

High HCL gel contains 1.0 ml concentrated (28%) HCL

Experiment No. 2 PNP Junction (low HCL)



P gel = 1 cm thick X 1.8 cm wide X 1.6 cm long

N gel = 1 cm thick X 1.8 cm wide

I_1 = emitter circuit current with collector circuit open.

I_2 = collector circuit current with emitter circuit open.

I_E = emitter circuit current with both circuits closed.

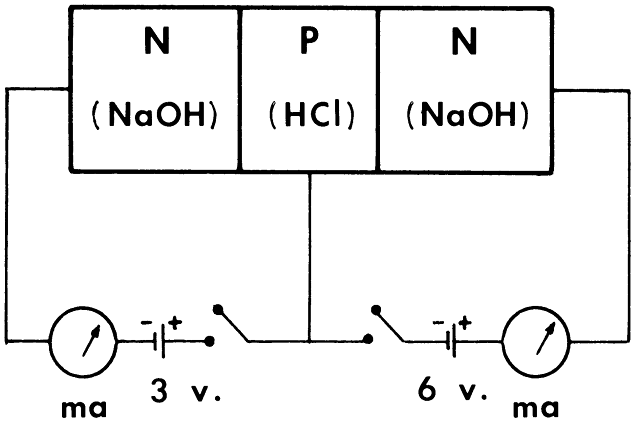
I_c = collector circuit current with both circuits closed.

I_g = current gain, V_g = voltage gain,

P_g = Power gain, R_g = Resistance gain.

Length of base,cm	I_1ma	I_2ma	$I_E$ma	$I_c$ma	I_g	R_g	V_g	P_g
2.5	2.3	2.8	5.5	6.7	1.22	1.77	2.16	2.64
2.3	1.8	1.8	6.1	7.4	1.21	2.0	2.42	2.92
1.8	1.5	1.7	6.1	7.6	1.25	1.76	2.2	2.76
1.6	1.4	1.6	6.8	8.5	1.25	1.75	2.18	2.74
1.2	1.4	1.7	7.9	9.5	1.20	1.65	1.98	2.38
0.7	1.4	1.5	8.7	9.9	1.24	1.87	2.32	2.88
0.5	1.5	1.9	9.3	11.7	1.15	1.58	1.82	2.08

Experiment No. 3   NPN Junction (low HCL)

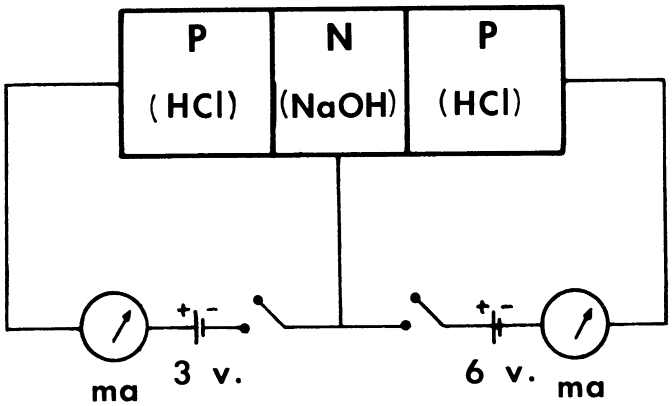


N gel = 1 cm thick X 1.7 cm wide X 1.5 cm long

P gel = 1 cm thick X 1.7 cm wide

Length of base, cm	I_1ma	I_2ma	$I_E$ma	$I_C$ma	I_g	R_g	V_g	P_g
1.6	4.4	8.4	8.2	10.4	1.27	1.05	1.33	1.74
1.2	4.4	8.0	9.1	12.0	1.32	1.1	1.45	1.91
0.9	4.0	8.0	9.5	10.5	1.1	1.0	1.1	1.21
0.6	2.6	7.4	7.5	9.0	1.2	0.704	0.842	1.01
0.4	1.6	7.0	8.1	9.7	1.2	0.456	0.548	0.65

Experiment No. 4 PNP Junction (high HCL)

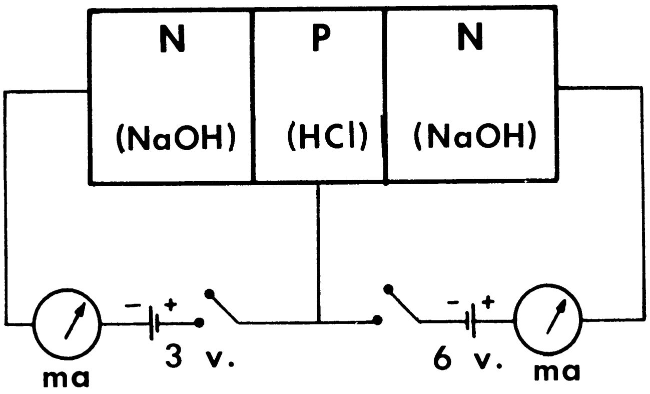


N gel = 1.25 cm thick X 1.7 cm wide

P gel = 1.25 cm thick X 1.7 cm wide X 1.0 cm long

Length of base, cm	I_1ma	I_2ma	$I_E$ma	$I_c$ma	I_g	R_g	V_g	P_g
1.4	2.4	1.6	15.0	16.5	1.1	3.0	3.30	3.62
1.2	2.4	2.2	13.3	16.0	1.2	2.18	2.62	3.14
0.9	2.1	1.6	13.9	16.5	1.19	2.62	3.12	3.72
0.4	2.4	0.9	15.8	18.0	1.14	5.32	6.08	6.94

Experiment No. 5 NPN Junction (high HCL)

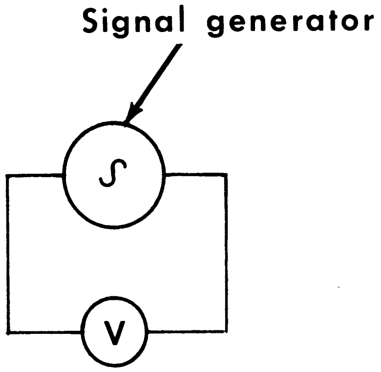


N gel = 1.4 cm thick X 2.2 cm wide X 1.25 cm long

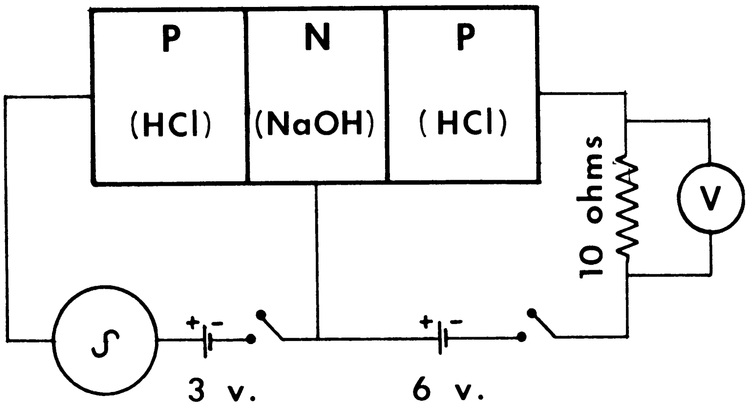
P gel = 1.4 cm thick X 2.2 cm wide

Length of base	I_1ma	I_2ma	$I_E$ma	$I_c$ma	I_g	R_g	V_g	P_g
1.3	2.4	12.3	12.6	15.9	1.26	0.390	0.491	0.620
1.0	3.3	12.0	13.1	16.0	1.22	0.550	0.672	0.820
0.6	3.1	12.1	12.5	16.2	1.30	0.712	0.666	0.866
0.4	1.5	12.4	14.2	17.4	1.23	0.242	0.296	0.366

Experiment No. 6 PNP Junction (low HCL)



Calibrations



Runs for frequency response

N gel = 1.0 cm thick X 3 cm wide X 0.5 cm long

P gel = 1.0 cm thick X 3 cm wide

Calibration for run No. 1 0.5 v.a.c. signal

Frequency cycles per second	Signal voltage
20	0.52
40	0.50
60	0.49
100	0.49
200	0.51
2,000	0.50
1,000	0.49
500	0.49
250	0.50
200	0.50
2,000	0.50
4,000	0.50
10,000	0.52
20,000	0.68
15,000	0.58

Run No. 1

Emitter bias voltage 0.5 v.a.c. (nominal)
Emitter bias voltage 3 v.d.c.
Collector bias voltage 6 v.d.c.

Frequency, cycles per second	Collector, a.c. volts	Corrected collector, a.c. volts
18	0.105	0.101
200	0.130	0.127
2,000	0.350	0.350
1,000	0.260	0.266
300	0.140	0.140
200	0.120	0.120
150	0.11	0.110
20,000	0.35	0.250
10,000	0.32	0.308
5,000	0.30	0.300
3,000	0.29	0.290
2,000	0.27	0.270

Calibration for run No. 2 1.5 v.a.c. (nominal)

Frequency, cycles per second	A.C. Volts
20	1.5
50	1.48
100	1.45
200	1.52
2,000	1.50
1,000	1.44
500	1.45
200	1.48
2,000	1.49
5,000	1.49
10,000	1.58
15,000	1.8
20,000	2.15

Run No. 2

Emitter bias voltage	1.5 v.a.c. (nominal)
Emitter bias voltage	3 v.d.c.
Collector bias voltage	6 v.d.c.

Frequency, cycles per second	Collector, a.c. volts	Corrected collector, a.c. volts
20	0.38	0.38
50	0.38	0.385
100	0.38	0.394
200	0.43	0.425
2,000	1.1	1.1
1,000	0.9	0.937
500	0.62	0.641
200	0.43	0.436
2,000	1.1	1.01
5,000	1.3	1.31
10,000	1.4	1.53
20,000	1.9	1.32

Calibration for run No. 3 3.0 v.a.c. (nominal)

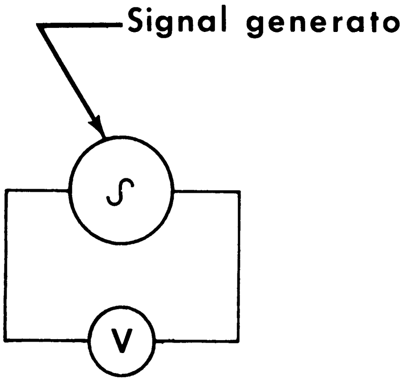
Frequency, cycles per second	A.C. Volts
20	3.1
50	3.1
50	2.99
100	2.96
200	3.09
2,000	3.05
1,000	2.95
500	2.98
200	3.00
2,000	3.00
5,000	3.00
10,000	3.20
15,000	3.60
20,000	4.20

Run No. 3

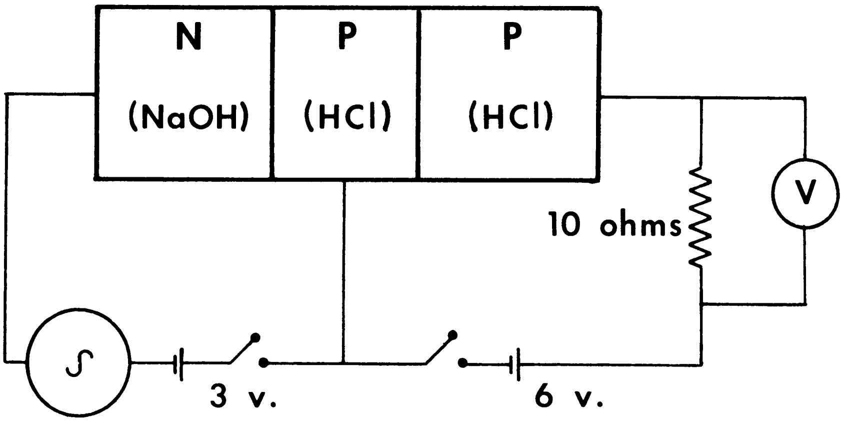
Emitter bias voltage	3 v.a.c. (nominal)
Emitter bias voltage	3 v.d.c.
Collector bias voltage	3 v.d.c.

Frequency, cycles per second	Collector, a.c. volts	Corrected collector, a.c. volts
20	0.48	0.465
50	0.48	0.481
100	0.52	0.527
200	0.60	0.582
200	0.60	0.60
500	0.92	0.925
1,000	1.33	1.35
2,000	2.1	2.06
2,000	2.1	2.10
5,000	2.6	2.60
10,000	2.87	2.69
15,000	3.2	2.66
20,000	3.7	2.64

Experiment No. 7 NPN Junction (low HCL)



Calibrations



Runs for frequency response

N gel = 1 cm thick X 2.7 cm wide X 1 cm long

P gel = 1 cm thick X 2.7 cm wide X 0.3 cm long

Calibration for run No. 1 same as calibration for run No. 3 Experiment No. 6.

Emitter bias voltage = 3 v.a.c. (nominal)
Emitter bias voltage = 3 v.d.c.
Collector bias voltage = 66 v.d.c.

Frequency, cycles per second	Collector a.c. volts	Corrected collector, a.c. volts
20	0.49	0.475
50	0.485	0.486
100	0.490	0.496
200	0.560	0.544
200	0.54	0.54
500	0.74	0.745
1,000	1.0	1.02
2,000	1.21	1.19
2,000	1.2	1.2
5,000	1.33	1.33
10,000	1.44	1.31
15,000	1.48	1.25
20,000	1.51	1.08

Calibration for run No. 2 1.5 v.a.c. (nominal)

Frequency, cycles per second	A.C. Volts
20	1.6
50	1.53
100	1.53
200	1.60
200	1.57
500	1.55
1,000	1.52
2,000	1.60
2,000	1.58
5,000	1.58
10,000	1.68
15,000	1.90
20,000	2.28

Run No. 2

Emitter bias voltage	1.5 v.a.c. (nominal)
Emitter bias voltage	3 v.d.c.
Collector bias voltage	6 v.d.c.

Frequency, cycles per second	Collector, a.c. volts	Corrected collector, a.c. volts
20	0.27	0.253
50	0.26	0.255
100	0.27	0.265
200	0.31	0.290
200	0.305	0.291
500	0.430	0.415
1,000	0.620	0.611
2,000	0.820	0.769
2,000	0.82	0.779
5,000	0.92	0.874
10,000	0.94	0.893
15,000	0.98	0.773
20,000	1.0	0.658

Calibration for run No. 3 0.5 v.a.c (nominal)

Frequency, cycles per second	A. C. Volts
20	0.52
50	0.50
100	0.49
200	0.52
200	0.50
500	0.50
1,000	0.49
2,000	0.50
2,000	0.50
5,000	0.50
10,000	0.53
15,000	0.585
20,000	0.69

Run No. 3

Emitter bias voltage 0.5 v.a.c. (nominal)
Emitter bias voltage 3 v.d.c.
Collector bias voltage 6 v.d.c.

Frequency, cycles per second	Collector, a.c. volts	Corrected collector, a.c. volts
20	0.08	0.0769
50	0.074	0.074
100	0.074	0.0755
200	0.084	0.0808
200	0.084	0.084
500	0.10	0.10
1,000	0.15	0.153
2,000	0.20	0.20
2,000	0.20	0.20
5,000	0.227	0.227
10,000	0.228	0.215
15,000	0.225	0.192
20,000	0.220	0.159

VIII. BIBLIOGRAPHY

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