and yet another

DEFINITIVE HANDBOOK OF TRANSISTOR MODELING

Part 1
subtitled "Modeling can be fun!"

Introduction

In many applications, computer aided design (CAD) is the best approach to analyzing a circuit. It has become quite clear from the present state and complexity of electronic circuit design that circuit simulation will be a necessary part of CAD for a long time to come. Since the inception of CAD, circuit designers have tried to effectively model the circuits that they wish to simulate in order to produce accurate results. However, with the limited availability of CAD models, it is impractical or inefficient to simulate circuits that only have ideal devices. At this point, the circuit designer may well wonder whether the difficulties of using CAD outweigh its advantages as a cheap and fast alternative to breadboarding. In any case, the problems of device modeling are not insurmountable and a good first cut model can be obtained from data sheet information and calculations made fairly quickly giving the designer an accurate device model for a wide range of applications.

The alternative method to modeling components from manufactureer's data sheets consists of spending long hours in the laboratory taking volumes of data and can be of little use if the data can not be translated into a form suitable for use with Spice or Spice parameters. In either case, after the data is reduced to a set of parameters, the model must then be tested and verified. Normally, this may take several iterations of parameter tweaking. Under normal circumstances, analyzing columns of data or the reading of plots of astericks can take many hours. Here's where Soft Scope can be a valuable help. The vast amount of menu-driven functions and data manipulation capabilities drastically decrease the time needed for data analysis and reduction. However, do not be lulled into a false sense of security. MODELING IS NOT EASY!!!!!! It can take the average engineer a minimum of 2-3 weeks to just become familiar with the procedures of modeling semiconductor devices.

Transistors

A large number of Bipolar transistors models exist for a variety of operational modes. However, for simulation programs such as Spice, a general nonlinear model must be used. The integral-charge model of Gummel and Poon which is accurate for static and dynamic simulations and for low and high power applications was chosen. This modified Gummel-poon model extends the original model to include several effects at high bias levels. The model will automatically simplify to the simpler Ebers-Moll model when certain parameters are not specified. Not all parameters need be specified everytime the model is used. The model parameters needed depend on the way the device is used. For instance, if a transistor is used only in a DC application, AC parameters are not needed, and incorporation of AC parameters will cause an unnecessary increase in run time. In order to provide the best results for circuit simulation and modeling follow the rule, "Use the simplest model possible".

The parameters necessary to define a model should be meaningful to an engineer and their determination should be straightforward and not time-consuming. However, for some parameters this is not always the case. Also, the analyst should not be concerned when some "nominal characteristics" cannot be fitted exactly by the Spice model equations. Examination of the device specifications and data sheets usually show a large variation in device characteristics. Below is a listing of the most significant BJT Parameters and when and when not to use each one of them.

BJT Model PArameter Applicability

Parameter	Use Default When:
IS,NF,BF	Insufficient data to determine NF.
ISE,NE	Transistor does not exhibit a "Non-Ideal" region. Transistor does not operate in the "Non-Ideal region.
RE	Insufficient data to determine RE or RE is lumped in with RB.
RB	Transistor does not operate at high enough base current for effect of RB to be significant.
IKF	Transistor does not show high injection effects, i.e. B does not decrease with high IC. Transistor does not operate in the high injection region.
VAF	Transistor operates with low VCE where early voltage effects are not significant.
RC	Transistor does not operate at high enough collector current for RC to have an effect.
BR,NR	Insufficient data to determine the reverse characteristics. Transistor is never reversed-biased in the particular application.
ISC,NC	Insufficient data to determine reverse characteristics. Transistor does not exhibit a reverse "Non-Ideal" characteristic.
IKR	Insufficient reverse data. Transistor does not exhibit a reverse high injection characteristic.
VAR	Insufficient reverse data. Transistor operates with low VEC where reverse Early effects are not significant.
CJE,MJE,VJE CJC,MJC,VJC	Transistor used only in a DC circuit application. If used in switching application, delay time is not critical.
TF,TR	Transistor used only in a DC circuit application.

Modeling Overview

A transistor model will only be as accurate as the parameters that describe it. However, accuracy is not always the most important criteria for a device model. MAKING A MODEL BEHAVE LIKE THE REAL DEVICE IS !!!!! Actual device measurements will provide accurate data for the calculation of accurate parameters, but indicate nothing about the distribution boundaries of the device parameters unless numerous devices are tested. The manufacturer's data sheets, on the other hand, yield parameter values which are often very inaccurate, yet they place a bounds on the parameter variations which may be used for best and worst case analysis. Data sheet information is generally very conservative and a number of key parameters can not be obtained from them, yet it provides a good first cut at a device model.

Both procedures, parameter extraction from manufacturer's data sheets or laboratory measurements, are described in detail in the following pages. In either case, curve fitting and customizing of a model for a particular circuit application will be necessary. In addition to the standard processes for finding device models (mathematical parameter extraction techniques) an effective and expedient technique for obtaining a device model is to use a trial and error method.

After obtaining accurate data curves from manufacturer's data sheets or laboratory measurements (Forward/Reverse Characteristics - Collector Characteristics - Rise/Fall Time Graphs - Transient Time Circuit Curves - Frequency Response Curves / See Spice examples at end of procedures) insert "Ball Park" parameters into models of Spice files which will generate the same type of curve. Then adjust or "tweak" the parameters until the SPICE generated curves are similar to the data sheet or laboratory curve.

The mastering of this technique requires a fairly good knowledge of how parameters interact, as well as, how each parameter affects the operation of the particular device. Throughout this manual and in the example of the 2N2907 at the end, we have tried to provide some good insight into this area.

** Note, it is almost impossible, if not useless, to try to exactly match the Spice generated data against the researched data. First of all, the operating point of the device will greatly affect the data recorded and unless exact conditions can be duplicated between the test circuit and the Spice circuit, the resulting parameters will be different. The difference is not do to the fact that one set of parameters is wrong, but to the fact that the operating conditions of each circuit are different. In order to use this method, an analyst should be familiar with other techniques of modeling, such as, parameter extraction from data sheets and laboratory measurements.

For more information and in depth studies of modeling techniques, the Spice user is directed to obtain the list of publications listed in the bibliography.

Background Information

The default BJT (Fig. 1 & 2) is an ideal transistor with a forward current gain of 100 and a reverse current gain of 1. It does not have a "non-ideal" region or a high injection region. Both the forward and reverse current gains are constant for any value of collector current. Both the base, collector, and emitter capacitances and resistances are zero. As can be seen by the extensiveness of the parameter list, the transistor model and its associated curves can be as simple or complex as required.

The DC model is defined by the parameters IS, BF, NF, ISE, IKF, and NE, which determine the forward current gain characteristics, and, BR, NR, ISC, IKR, and NC, which determine the reverse current gain characteristics and VAF and VAR, which determine the output conductance for the forward and reverse regions. Three ohmic resistances RB, RC, and RE are included. Base Charge storage is modeled by forward and reverse transit times TR, and TF and nonlinear depletion layer capacitances which are determined by CJE, VJE, and MJE for the B-E junction, CJC, VJC, and MJC for the B-C junction, and CJS, VJS, and MJS for the C-S (collector-substrate) junction. Of the 40 parameters used to characterize the transistor, 15 parameters (IRB, RBM, XTF, VTF, ITF, PTF, XCJC, CJS, MJS, VJS, XTB, XTI, KF, AF, and FC) are related to Flicker-Noise and higher order effects which are not ordinarily needed nor specified in most manufacturer's data sheets.

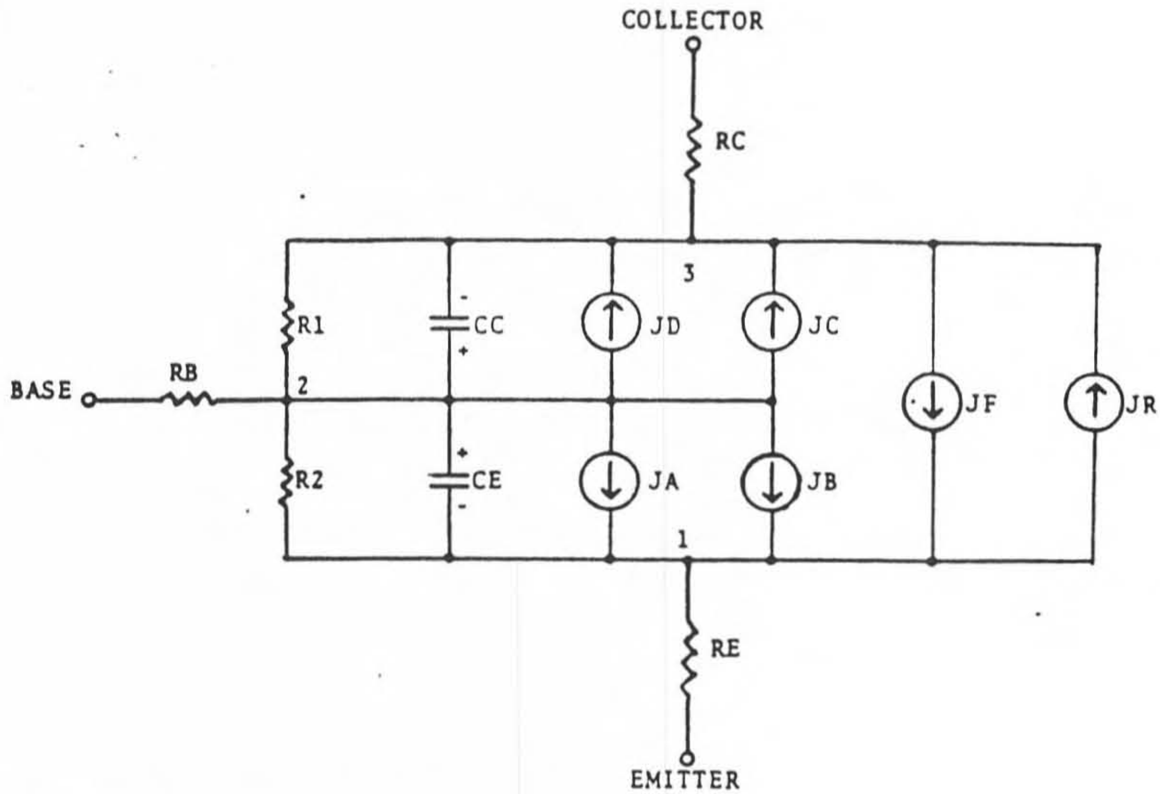
Methods for determination of model parameters from manufacturer's data sheets are shown next, followed by laboratory measurement techniques. The available data from sheets may not be as comprehensive as that required for a complete model and many device data sheets do not provide sufficient information to calculate the entire range of parameters. For instance, reverse DC characteristics may not be shown or the data that is may only be typical, minimum, maximum or limited in range. Data sheets from various manufacturer's may have to be pieced together in order to provide a full set of data. In any case, the best information is likely to be found on the data sheets of the manufacturer who first made the part. That might not be of much help, especially if you don't know who first made the device, but it brings up an important point. Since device modeling is a task usually given to a "NEW - HIRE", it is recommended that the advise of a Senior Engineer with experience be sort after when a difficult problem is encountered. Get used to asking questions, because your going to have a lot of them. By the way, this paper was written by "NEW - HIRE'S" and we assure you that our Senior Engineer runs everytime he see's us because he knows there's a barrage of questions coming at him.

The techniques and formulas presented in the procedures section of the manual are for a NPN transistor. In order to make them applicable to PNP transistors just put a negative sign in front of any voltage used. Also, the example at the end of the manual uses a PNP transistor to clarify this point.

INTRODUCTION:

SPICE contains "built-in" equations for the Gummel-Poon model of a PNP Bipolar Junction Transistor. The model diagram and defining equations are listed in the following section. Of the 40 parameters used to characterize the transistor, 25 of them have have been calculated to customize the Gummel-Poon model to simulate the 2N2907A PNP BJT. The other 15 parameters (IRB, RBM, XTF, VTF, ITF, PTF, XCJC, CJS, MJS, VJS, XTB, XTI, KF, AF, FC) are related to Flicker-Noise and higher order effects which are not ordinarily specified in manufacturer's data.

BACKGROUND:



JA = non-ideal forward region base current
JB = ideal forward region base current
JC = non-ideal inverse region base current
JD = ideal inverse region base current
JF = forward region dependent current
JR = inverse region dependent current
CC = collector junction capacitance
CE = emitter junction capacitance
RC = collector bulk resistance
RB = base bulk resistance
RE = emitter bulk resistance
R1 = collector-base junction leakage resistance*
R2 = emitter-base junction leakage resistance*

* not included in SPICE model

Defining Equations:

$$JA = ISE \left[e^{\left(\frac{V_{B'E'}}{NE(V_t)}\right)} - 1 \right]$$

SPICE model parameter ISE = C2xIS
Default ISE = 0
where: C2 = non-ideal normalizing coefficient
IS = saturation current

SPICE model parameter NE = emitter junction grading constant
Default NE = 1.5

$V_{B'E'}$ = base-emitter junction voltage (voltage from 2 to 1 on the model diagram)

$V_t = \frac{kT}{q} \approx 0.026$ volts at 27°C (300°K)

$$JB = \frac{IS}{BF} \left[e^{\left(\frac{V_{B'E'}}{NF(V_t)}\right)} - 1 \right]$$

SPICE model parameter IS = saturation current
Default IS = $1x10^{-16}$
SPICE model parameter BF = ideal maximum forward ß
Default BF = 100
SPICE model parameter NF = forward current emission coefficient
Default NF = 1

$$JC = ISC \left[e^{\left(\frac{V_{B'C'}}{NC(V_t)}\right)} - 1 \right]$$

SPICE model parameter ISC = C4xIS
Default ISC = 0
where: C4 = non-ideal normalizing coefficient
IS = saturation current
SPICE model parameter NC = base-collector grading constant
Default NC = 2
$V_{B'C'}$ = base-collector junction voltage
(voltage from 2 to 3 on the model diagram)

$$JD = \frac{IS}{BR} \left[e^{\left(\frac{V_{B'C'}}{NR(V_t)}\right)} - 1 \right]$$

SPICE model parameter BR = ideal maximum reverse ß
Default BR = 1
SPICE model parameter NR = reverse current emission coefficient
Default NR = 1

$$JF = \frac{IS}{QB}\left[e^{\left(\frac{V_{B'E'}}{NF(V_t)}\right)} -1\right]$$

QB (See below.)

$$JR = \frac{IS}{QB}\left[e^{\left(\frac{V_{B'C'}}{NR(V_t)}\right)} -1\right]$$

$$QB = \frac{Q1}{2}\left(1+\sqrt{1+4Q2}\right)$$

$$Q1 = \frac{1}{1 - \frac{V_{B'C'}}{VAF} - \frac{V_{B'E'}}{VAR}}$$

SPICE model parameter VAF = forward early voltage
Default VAF = ∞
SPICE model parameter VAR = reverse early voltage
Default VAR = ∞

$$Q2 = \frac{IS}{IKF}\left[e^{\left(\frac{V_{B'E'}}{NF(V_t)}\right)} -1\right] + \frac{IS}{IKR}\left[e^{\left(\frac{V_{B'C'}}{NR(V_t)}\right)} -1\right]$$

SPICE model parameter IKF = corner for forward ß high current roll-off
Default IKF = ∞
SPICE model parameter IKR = corner for reverse ß high current roll-off
Default IKR = ∞

$$CE = \frac{CJE}{\left(1- \frac{V_{B'E'}}{VJE}\right)^{MJE}} + TFF \times \frac{IS}{V_t}\left[e^{\left(\frac{V_{B'E'}}{NF(V_t)}\right)}\right]$$

where:

SPICE model parameter CJE = zero-bias base-emitter capacitance
Default CJE = 0
SPICE model parameter VJE = base-emitter junction contact potential
Default VJE = .75
SPICE model parameter MJE = base-emitter junction exponential factor
Default MJE = .33

$$TFF = TF\,(1+XTF)\left(\frac{IF}{IF+ITF}\right)^2\left[\epsilon^{\left(\frac{V_{B'C'}}{1.44\ VTF}\right)}\right]$$

$$IF = IS\left[\epsilon^{\left(\frac{V_{B'E'}}{NF(V_t)}\right)}-1\right]$$

SPICE model parameter TF = ideal forward transit time
Default TF = 0
SPICE model parameter XTF = coefficient for bias dependence of TF
Default XTF = 0
SPICE model parameter VTF = voltage describing base-collector voltage dependence of TF
Default VTF = 0
SPICE model parameter ITF = high-current parameter for effect on TF
Default ITF = 0

$$CC = \frac{CJC}{\left(1 - \frac{V_{B'C'}}{VJC}\right)^{MJC}} + TR \times \frac{IS}{V_t}\left[\epsilon^{\left(\frac{V_{B'C'}}{NR(V_t)}\right)}\right]$$

where:

SPICE model parameters:
CJC = base-collector zero-bias depletion capacitance
Default CJC = 0
VJC = base-collector junction contact potential
Default VJC = .75
MJC = base-collector junction exponential factor
Default MJC = .33
TR = ideal reverse transit time
Default TR = 0

Modeling Transistors From Manufacturers' Data Sheets

1. NF Forward Current Emission Coefficient

   NF's normal value is between 1 and 2. If data cannot be obtained it is proper to assume a value of 1. Its value will effect the saturation current IS.

   Use a plot of IC vs. VBE (Data sheet "ON" plot)

   $$NF = VBE1 - VBE2/(VT*(\ln(IC1/IC2))) \quad \text{Eq. \#1}$$

2. IS Transport Saturation Current

   The saturation current is determined by the doping profile and emitter-base junction cross-sectional area. A typical value is 10E-16 Amps, however, a variation of several orders of magnitude is not uncommon. The saturation currents (IS, ISE, ISC) will affect among other things the slope of the forward DC curves (IC and IB vs. VBE). (Fig. 3)

   A data sheet "ON" voltage plot yields a point where VBE=VCE, find IC and insert in the equation below. ***SEE NOTE AT BR***

   Measure VBE to at least three decimal places.

   $$IS = IC/(\exp(VBE/NF*VT)-1) \text{ or}$$
   $$= IE/(\exp(VBE/NF*VT)-1) \quad \text{where VBE=VCE and currents are small (linear region)}$$

3. BF Ideal Maximum Forward Beta

   BF is the value of B in the ideal region of the transistor. Although this parameter looks easy to find, it must be determined by trail and error because many transistors do not have a clear ideal region. Beta variations produced by changes in collector current occur in three regions. (low injection region, ideal region, and high injection region Fig. 4)

   Data sheets normally give forward current gain information or normalized current gain information. Using this data, the analyst can determine the desired value of BF which will yield either a minimum, typical, or maximum current gain model.

   To find BF plot B = IC/IB vs. ln IC

4. BR Ideal Maximum Reverse Beta

Determine BR and NR in a manner similar to that used for BF and NF in the forward region. Data must be usually measured because manufacturer's data sheets normally do not include reverse characteristics.

Obtain data of IE and IB vs. VBC over a large range of base currents. BR can be determined from a point in the ideal region. (Cir. 1)

NOTE IS is a fundamental parameter that is related directly to the zero-bias majority-carrier profile in the base. IS is the extrapolated intercept current of the graph of log(IC) vs. VBE in the forward region, as well as, log(IE) vs. VBC in the reverse region. Compare the IS values determined from the forward and reverse characteristics. (Substitute IE for IC, VBC for VBE and NR for NF in equation #1) If these values are not reasonably close and a good fit of both forward and reverse characteristics cannot be obtained with a single value of IS chosen, then some part of the measured of calculated data is in error. Re-check all data before proceeding.

5. NR Reverse Current Emission Coefficient

*See Lab Techniques

6. NE B-E Leakage Emmision Coefficient

May be found from previous data acquisition. Looking at the slope of the non-ideal region of the log(B) vs. log(IC) curve, NE may be determined from the slope of the line in the non-ideal region. (Fig. 5)

NE = 1/(slope - 1) where

Slope = log(B1)-log(B2)/(log(IC1)-log(IC2))

*See Lab Techniques

7. ISE B-E Leakage Saturation Current

ISE may be found from a point on the IB vs. VBE curve.

A. ISE = IB1/(exp(VBE1/NE(VT))-1) *See Lab Techniques

or B. ISE = C2(IS) where

C2 = ((IL/IS)(1-(1/NE))/BF and
IL = to the collector current where B = BF/2 in the non-ideal region.

or C. ISE = IS/@f where

@f = B/(1+B) where B is in the normal active region

8. NC B-C Leakage Emission Coefficient
*See Lab Techniques

9. ISC B-C Leakage Saturation Current

*See Lab Techniques

10. RB Zero Bias Base Resistance

RB models the resistance between the base region and the base terminal. There are several ways to calculate RB, each of which may provide a different answer. RB is a difficult parameter to measure because it is modeled as a constant resistance although it is actually a distributed variable resistance. RB's value is dependent on the operating point of the transistor. The best test method and value to chose is dependent on your application, therefore the application should determine the test measurement technique. Its value can range from 10 ohms (microwave devices) to several kilohms.

An alternative method which can be derived from a data sheet "ON" data plot provides an RB value where RE is ignored and the effects of RE are lumped together with the effects of RB.

Using RB = VBE2-VBE1/IB1

When using a data sheet use VBEsat and IB at the highest value of collector current shown. This curve is usually shown for IC/IB = 10. Use the formula;

RB = (VBEsat - .6)/IB where .6 represents a diode

voltage drop and IB is the highest available base current on the data sheet.

11. RE Emitter Resistance

RE is a constant valued resistor which models the resistance between the emitter region and the emitter terminal. A typical value of RE is 1 ohm. RE may also be accounted for by properly calculating RB.

*See Lab Techniques

12. RC Collector

RC models the resistance between the collector region and the collector terminal. RC is actually a resistance dependent on collector current and base-collector voltage, but is usually modeled as a constant valued resistor. Therefore, the biggest problem in obtaining a value for RC is not how to measure it but which value to use. RC decreases the slope of the curves in the saturation region for low collector-emitter voltages. A typical value is 10 ohms or less.

RC may also be estimated from the "ON Voltage" figure of the data sheet. Use VCEsat and IC at the highest collector current shown.

RC = (VCEsat - .2)/IC   where

.2V is a typical value of ideal saturation voltage allowing the ohmic voltage drop to be estimated.

See Lab Techniques

13. IKF Corner for Forward Beta High Current Roll-off

IKF is the value of IC at the transition between the ideal region and the high injection region. IKF can be determined from a plot of lnBF vs. lnIC. and is equal to the value of the collector current at the point where B is 1/2 its maximum value (BF/2). Some trial and error is required in selecting BF and IKF to fit the log(IB) and log(IC) vs. VBE characteristic. (Fig. 6)

14. IKR Corner For Reverse Beta High Current Roll-off

IKR is the value of IE at the transition region between the ideal and the high injection reverse regions. It is also the value of IE at the point where B is equal to BR/2 near the high injection region. It effects the shape of the BR curve and the reverse current gain.

15. VAF Forward Early Voltage

VA is a parameter used to model base width modulation effects (the early effects). A typical value is 100 volts. Where data sheets do not give a set of collector characteristics the following may be used to estimate VAF. Using the normalized DC current gain characteristics which yield data at two VCE voltages, VAF can be found by a plot of IC vs. VCE for different currents. (Fig. 7) If a set of collector characteristics is available, extrapolate all of the active region portions of the curve to the left. The VCE x-axis intercept is then the VAF parameter (See Lab. Since the extrapolations will usually be over a wide range of voltages, an average must be taken.

16. VAR Reverse Early Voltage

Measure the set of emitter characteristics IE vs. VBC at several constant values of IB in the reverse region.

VAR is the negative of the extrapolated intercept, VBC, of IE vs. VBC on the VBC axis.

17. CJE B-E Zero-Bias Depletion Capacitance
VJE B-E Built-in Potential
MJE B-E Junction Exponential Factor

These next six parameters describe the transition capacitance associated with the collector-base junction or the base-emitter junction. The two capacitances, CJE and CJC, are nonlinear and voltage dependent. They are also necessary if any AC models are to be affective. The base-emitter junction depletion capacitance parameters can be obtained from measurements of junction capacitance vs. reverse base-emitter voltage. (CE vs. VBE). It may be necessary to subtract out a constant capacitance from the measured value. This extra capacitance term is usually around .5PF and is the stray capacitance associated with the transistor package. Manufacturer's data sheets usually show capacitance vs. reverse voltage (CE vs. VBE reverse) as the Cib curve. The VJ parameters are normally .7 for silicon devices and the MJ parameters are equal to .5 for an abrupt junction and .333 for a linearly graded junction. Since most junctions fit between these two, MJE or MJC is from .333 to .5. A typical value of CJE or CJC is about 20PF.

*See Lab Techniques

1. CJE is the capacitance value at VBE=0 or it can be calculated from one point on the CE vs. VBE curve.

CJE = CE1*((1-(VBE1/VJE)**MJE)

2. Find the values CE (Junction capacitance) at various reverse bias voltages. Measurements are made between the base terminal and the emitter terminal with the collector open.
3. Using the formula:

   CE = CJE/(((1-(VBE/VJE))**MJE)

   assume a value for VJE in the range of .6 to 1 volt.
4. Plot CE vs. (VJE-VBE) on log-log paper
5. If the line is straight, then the assumed value of VJE is correct.
6. If the line is not straight, then assume another value for VJE and repeat steps 4 and 5.
7. When a straight line is obtained determine the MJE from two points by the following equation:

   -MJE = (ln(CE1)-ln(CE2))/(ln(VJE-VBE1)-ln(VJE-VBE2))

NOTE: Remember that the VBE values are negative since the data points are from the reverse bias region.

18. CJC B-C Zero-Bias Depletion Capacitance
    VJE B-C Built-in Potential
    MJE B-C Junction Exponential Factor

    The procedures for finding these parameters are exactly the same as for CJE, VJE, and MJE except the measurements should be of Junction capacitance vs. reverse base-collector voltage (CE vs. VBC). The measurements should be made between the base terminal and the collector terminal with the emitter open. Data sheets usually show the CC vs. VBC reverse curve as the Cob vs. Reverse voltage plot or you can use CE vs. VBC data and the equations:

    CC = CJC/((1-(VBC/VJC))**MJC)

    -MJC =(ln(CC1)-ln(CC2))/(ln(VJC-VBC1)-ln(VJC-VBC2))

    CJC is again the capacitance value at VBC=0 or

    CJC = CC1*(((1-(VBC1/VJC))**MJC)

19. TF Forward Transit Time

The forward transit time can be determined from the data sheet TURN-ON TIME figure which shows the 10% to 90% rise time, tr vs. IC. Use two points ICo which is IC near zero, and IC1 which is IC at some value greater than zero. TF is greatly dependent on

A. IC1, the collector current
B. IB1, the base current at IC1 and
C. BF1, the forward current gain at IC1

Data sheets usually show tr vs. IC1 with IC1/IB1 = 10 However, the analyst may wish to take a measurement for IC1 at the anticipated value of collector current for his particular application. Manufacturer's usually show a test circuit for rise time measurements.

Use the formula: TF = (tr/2.2)(1/(BF+1))

20. TR Reverse Transit Time

The reverse transit time can be determined from the data sheet TURN-OFF TIME figure which shows the storage time, ts vs. collector current, IC. ts is the time for the collector current to fall from some value, ICo, to 90% of that value when the base current is suddenly reversed from its initial value, IBo, to IB1, where IB1 = -IBo. Like TF, TR is dependent on the selected values of ICo, IBo, IB1, and the reverse current gain, BR, at the chosen ICo. Manufacturer's data sheets usually show ts vs. ICo at ICo/IC1 = 10. Again the analyst may prefer to take a measurement for ICo at the anticipated value for the particular application. Manufacturer's usually show a circuit for storage time measurements.

Use the formula:

TR = (1/(BR+1))[ts/(ln((IBo-IB1)/(ICo/(BF-IB1))))]

Inclusion of Breakdown Characteristics

Breakdown can be simulated by including two current generators, which are EXTERNAL to the device model.

Needed at the parameters

BVcbo - Collector-to-Base breakdown voltage
BVebo - Emitter-to-Base breakdown voltage
Nc - Collector-Base Multiplication region constant
Ne - Emitter-Base Multiplication region constant

Typical values for BVcbo and BVebo are from less than 5 volts to greater than 2000 volts. Nc and Ne are typically between 2 and 4 for silicon devices. Manufacturer's data sheets normally list the minimum breakdown voltages.

Use the formulas: Nc = logBF/(log(BVcbo/BVebo))
Ne = logBI/(log(BVcbo/BVebo))

where Mc = 1/[1-((Vbc/BVcbo)**Nc)]
and Me = 1/[1-((Vbe/BVebo)**Ne)]

yielding IBC = IC(Mc - 1)
IBE = IE(Me - 1)

FIG.1 Ideal log(IC) & log(IB) vs. Vbe Ideal βf vs. IC

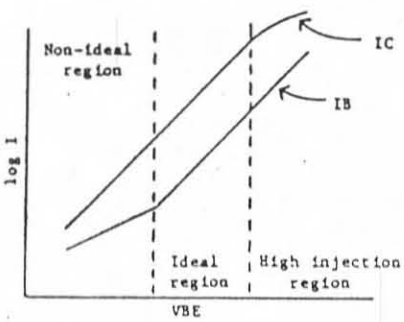


FIG.2 Actual log(I) vs. Vbe

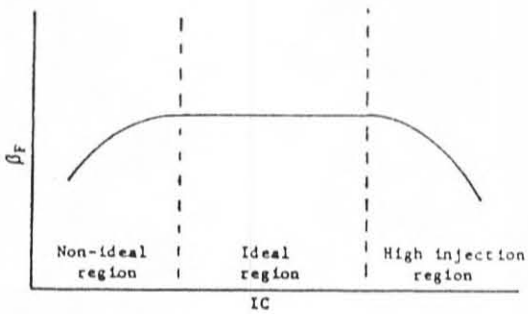


FIG.4 Actual βf vs. IC

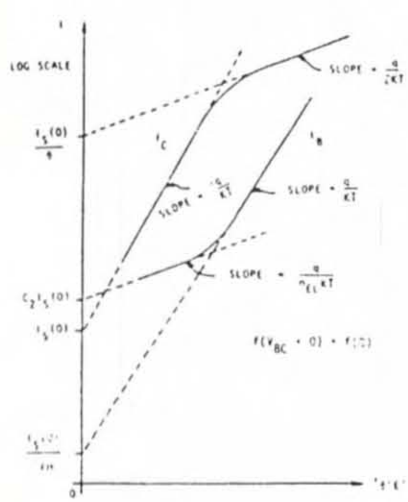


FIG.3 IS Curves

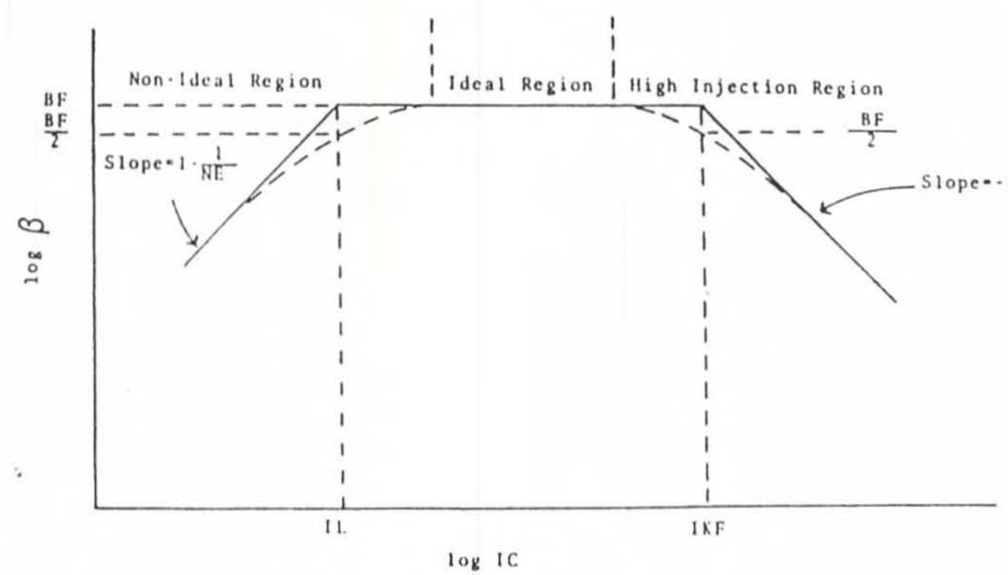
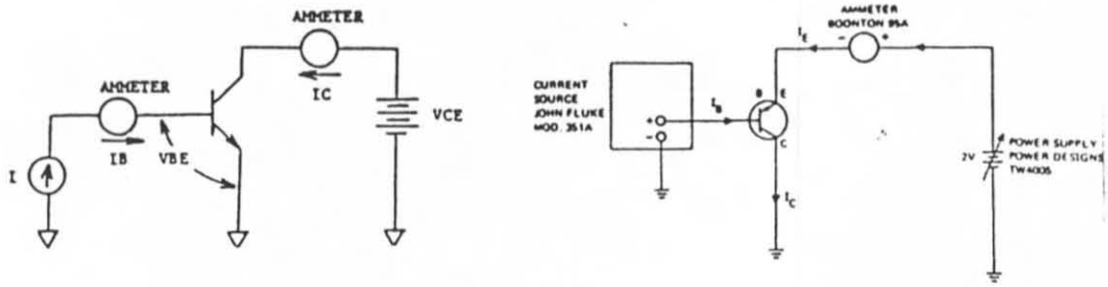


FIG.5 & 6



CIR.1

Forward & Reverse

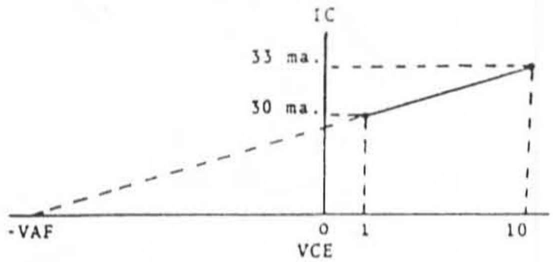
Current Measurements

Point #1

For VCE = 10 volts, the normalized h_{FE} = 1.1 in the IC range of 20 to 30 ma.

Point #2

For VCE = 1 volt, the normalized h_{FE} = 1.0 in the IC range of 20 to 30 ma.



$$\frac{IC1-IC2}{VCE1-VCE2} = \frac{IC1-0}{VCE1-(-VAF)}$$

or

$$VAF = IC1 \times \left(\frac{VCE1-VCE2}{IC1-IC2}\right) - VCE1$$

FIG.7 VAF Meas.

Modeling Transistors From Laboratory Measurements

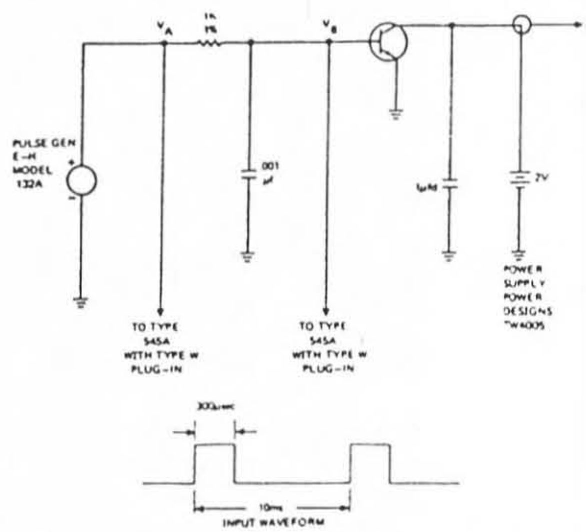
with 2N2907 PNP Transistor Example

RECOMMENDATIONS FOR MODELING and LAB DATA GATHERING:

Problems with data taking will be encountered at every stage in the modeling process. An analyst must be extremely careful in every step. Seemingly accurate data may actually be in error, caused by what may be considered an insignificant detail. A good indication of accurate data can be found in the fact the when measurements are repeated, the data is reliable and repeatable. Some of the problems to watch for are:

1. Temperature variations At the low levels of current and voltage measurement a change in temperature will greatly affect the data taken. Also, at high current levels, most devices will begin to heat up. This will cause inaccurate data to be measured. If laboratory data is to repeatable and reliable. Care must be taken to record the temperature and keep it reasonably steady. At high current levels, it is recommended that input voltages and currents be pulsed with a duty cycle of less than 5%. See figure

2. Impedances of measuring equipment
When measuring low currents care must be taken to evaluate the effects of loading on a test circuit by instruments.



Test Circuit For High Current Levels

3. Variations among devices
   It is best to evaluate a number of the same devices when measuring data. Such a sampling and the information it provides will help to filter out any extremes in the data patterns that would lead to erroneous conclusions. Also, if a device is accidently overstressed, its subsequent data that is yielded should come under additional scrutiny.

4. Circuits in this manual are presented for a guide only. Various sources of information on modeling may present circuits that appear to be different, however, the data that is yielded should be consistent no matter which topology is used. In practice, however, this is not always the case. The test circuit that provides the most consistent (repeatable) and seemingly accurate data is the best.

5. When testing for parameters, always choose operating conditions that will resemble the model application's operating conditions.

6. Because the Bipolar Junction Transistor is very complex and non-linear, no single set of model parameters will fit all applications. It is important to know what the model's uses will be.

7. The ultimate goal of any good model is to reproduce the same charactersitics as the real device. Thus, after a parameter is found using a test method, it is perfectly acceptable to "tweak" that parameter to get the end result.

8. The default values should be used whenever possible. This will save in computing time.

9. When using the model, always keep in mind the limitations imposed onto the model. A model is only as good as the parameters that specify it and every parameter has limits to its usage.

10. The order in which these parameters are presented should be the order in which they are sought. In many cases, the value of a previous parameter is necessary to obtain the one being found.

11. Use as simple a model as possible. It is redundant to try and get an exact model when an approximate one will suffice.

12. As each paramter is found it should be added to the SPICE model and tested to see if it contributes positively (or negatively) to the overall requirements.

MODELING:

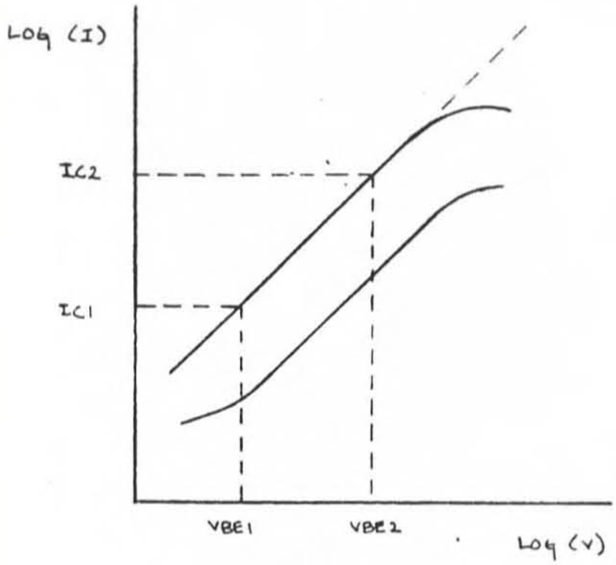
PARAMETER: NF

DEFINITION: forward current emission coefficient

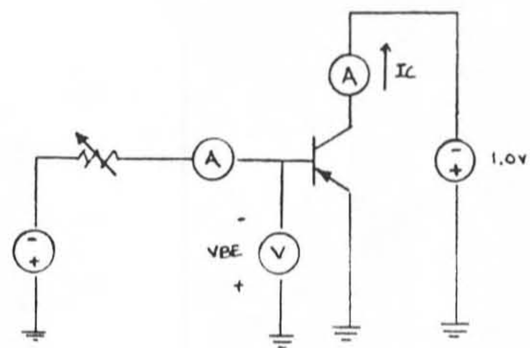
MEASURED VALUE: 1.21
TYPICAL VALUE: 1.0
SPICE DEFAULT: 1.0

METHOD:

$$NF = [VBE2-VBE1] / [(Vt)LN(IC2/IC1)]$$



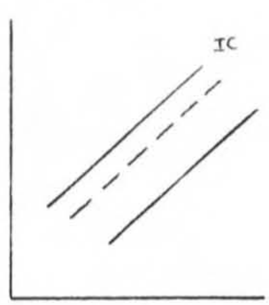
CIRCUIT DESIGN:



forward DC characteristics

NOTE: 1. VBE1,VBE2,IC1,IC2 are found from the straight line portion of the IC vs. VBE curve.
2. Vt = kT/q =0.026 volts at 300K

EFFECT OF PARAMETER:
NF affects IC in the forward DC, ideal region. As NF is increased, the curve of IC shifts downward.



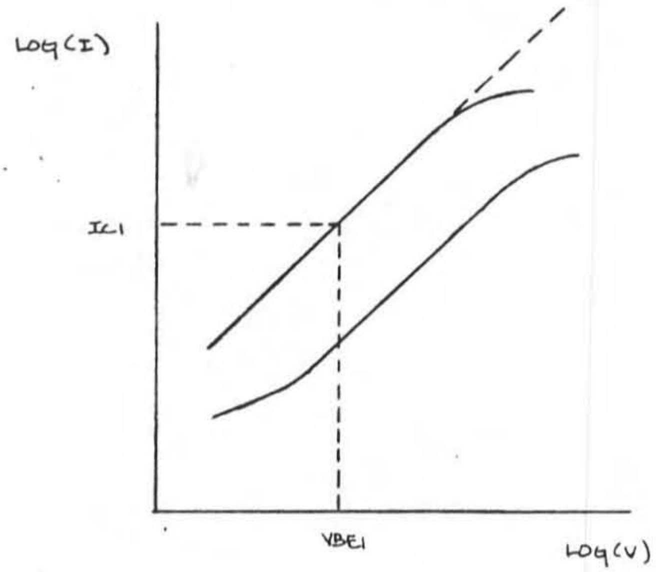
PARAMETER: IS

DEFINITION: transistor saturation current

MEASURED VALUE: 1.10 E-12 amperes
TYPICAL VALUE: 1.0 E-16 amperes
SPICE DEFAULT: 1.0 E-16 amperes

METHOD:

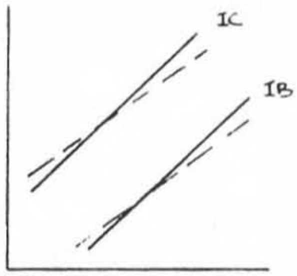
$$IS = IC1 / \{\exp[VBE1/(NF)(Vt)]-1\}$$



NOTE: 1. IC1 and IB1 are taken from the straight line portion of IC vs. VBE.
2. NF must be found before IS can be calculated.

CIRCUIT: use the FORWARD DC CHARACTERISTIC CIRCUIT SET-UP

EFFECT OF PARAMETER:
IS greatly affects the forward and reverse characteristic curves in the DC operation. The slopes of both IC and IB in the linear region are changed as IS is increased or decreased.



PARAMETER: EG

DEFINITION: energy gap of the semiconductor material

MEASURED VALUE: 1.1 e-volts (since silicon)
TYPICAL VALUE: 1.1 e-volts for silicon
.67 e-volts for germanium
.69 e-volts for Schottky-barrier devices
SPICE DEFAULT: 1.1 e-volts

PARAMETER: BR

DEFINITION: ideal maximum reverse beta

MEASURED VALUE: 11
TYPICAL VALUE: .5
SPICE DEFAULT: 1

METHOD:

The curve tracer was again used. The measurement of BR is identical with that of BF, the only difference is the emitter and collector pins were interchanged. Thus the collector current is actually the emitter current and the collector-emitter voltage is actually the emitter-collector voltage.

VERT	- collector current	1ma/div
HORIZ	- collector-emitter voltage	.5v/div
STEP	- base current	5ua/div

BR = reverse DC beta = IE/IB for a constant VEC

NOTE: 1. IE and IC should be measured at the operating point intended for use in the circuit.

EFFECT OF PARAMETER:

BR shifts the IB of the reverse DC ideal region in the same manner that BF did for the forward DC ideal region.

PARAMETER: BF

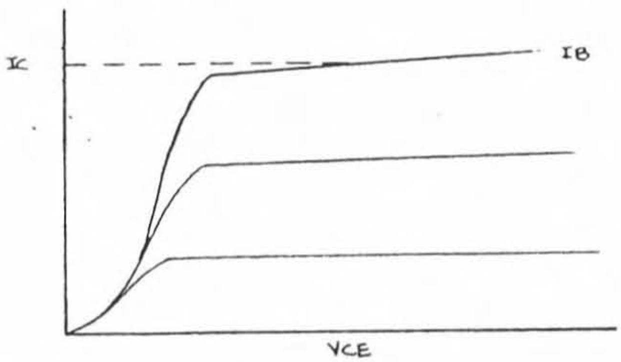
DEFINITION: ideal maximum forward beta

MEASURED VALUE: 202
TYPICAL VALUE: 100 - 300
SPICE DEFAULT: 100

METHOD:

A curve tracer was used to find BF. The settings of the curve tracer were,

VERT	- collector current	1ma/div
HORIZ	- collector-emitter voltage	.5v/div
STEP	- base current	5ua/div

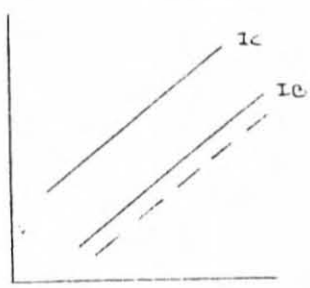


BF = forward DC beta = IC/IB for a constant VCE

NOTE: 1. IC and IB should be measured at the operating point intended for use in the circuit.

EFFECT OF PARAMETER:

BF shifts the forward DC ideal region's curve of IB. IB shifts with respect ot the location of IC. As BF is increased, the distance between IC and IB is increased.



PARAMETER: NR

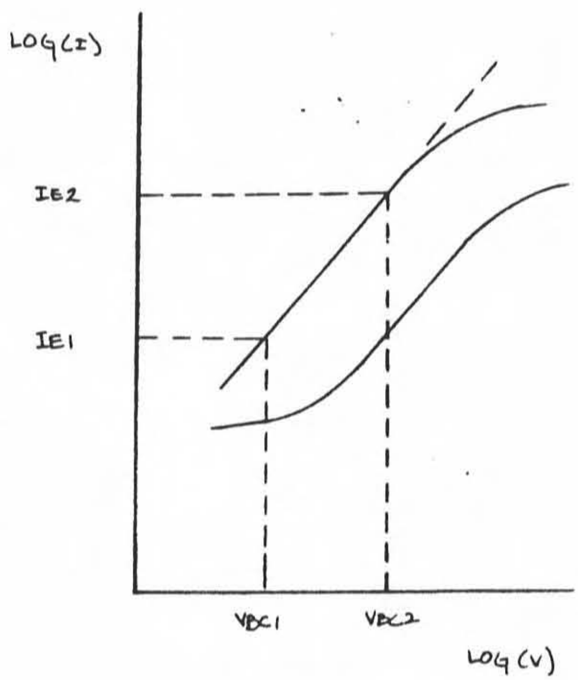
DEFINITION: reverse current emission coefficient

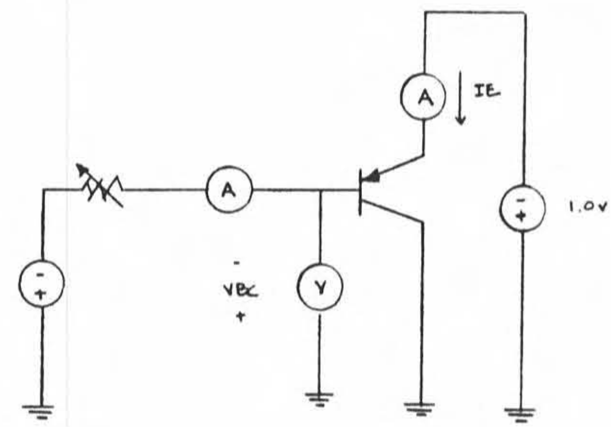
MEASURED VALUE: 1.04
TYPICAL VALUE: 1.0
SPICE DEFAULT: 1.0

METHOD:

$$NR = [VBC2-VBC1] / [(Vt)LN(IE2/IE1)]$$

CIRCUIT DESIGN:





reverse DC characteristics

NOTE: 1. VBC1, VBC2, IE1, IE2 are found from the straight line portion of the IE vs. VBC curve.

EFFECT OF PARAMETER:
NR affects IE (in the reverse DC ideal region) identically the same way NF affects IC (in the forward DC ideal region).

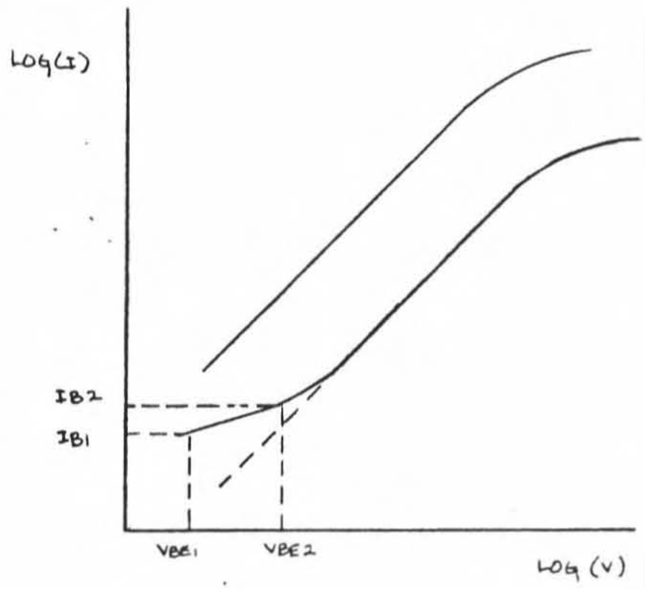
PARAMETER: NE

DEFINITION: base-emitter leakage emission coefficient

MEASURED VALUE: 1.92
TYPICAL VALUE: 2
SPICE DEFAULT: 1.5

METHOD:

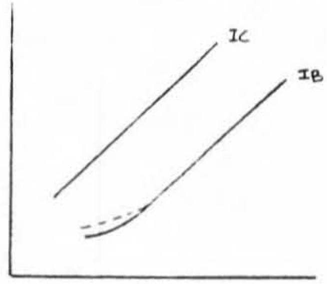
NE = [VBE2-VBE1] / [(Vt)LN(IB2/IB1)]



NOTE: 1. VBE1, VBE2, IB1, IB2 are found from the non-linear region of the IB vs. VBE graph.

CIRCUIT: use the FORWARD DC CHARACTERISTICS CIRCUIT SET-UP

EFFECT OF PARAMETER:
NE and ISE are responsible for forming the non-ideal region of IB in the forward DC curves. NE affects the curving of IB in the transition from ideal to non-ideal region.



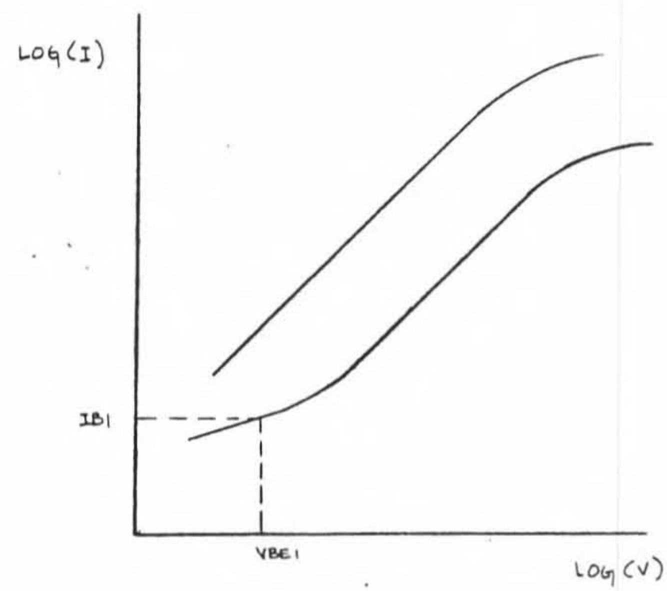
PARAMETER: ISE

DEFINITION: base-emitter leakage saturation current

MEASURED VALUE: 6.67 E-12 amperes
TYPICAL VALUE: 1 E-12 amperes
SPICE DEFAULT: 0 amperes

METHOD:

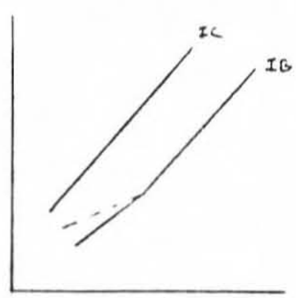
$$ISE = IB1 / [\exp(VBE1/NE(Vt))-1]$$



NOTE: 1. IB1, VBE1 are taken from the non-ideal region of the IB vs. VBE curve.
2. NE must be found first in order to calculate ISE.

CIRCUIT: use the FORWARD DC CHARACTERISTICS CIRCUIT SET-UP

EFFECT OF PARAMETER:
ISE determines the slope of the non-ideal region of IB when the transistor is forward DC biased.



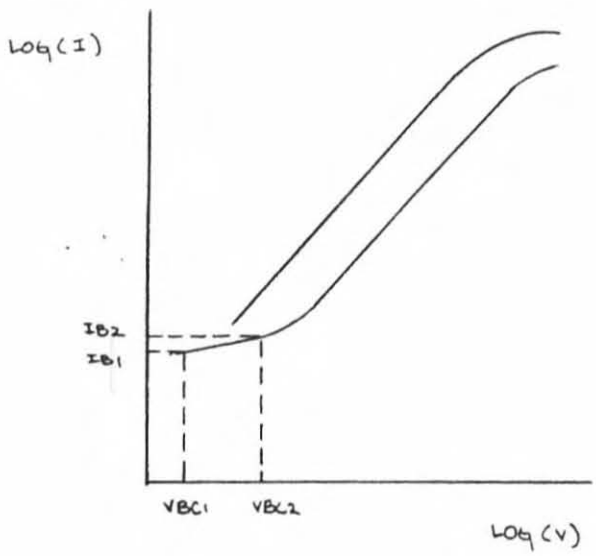
PARAMETER: NC

DEFINITION: base-collector leakage emission coefficient

MEASURED VALUE: 4.48
TYPICAL VALUE: 2.0
SPICE DEFAULT: 2.0

METHOD:

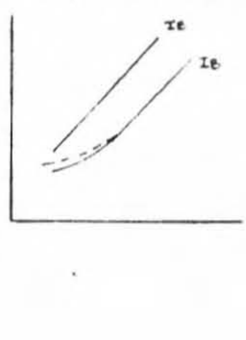
$$NC = [VBC2-VBC1] / [(Vt)LN(IB2/IB1)]$$



NOTE: 1. IB1, IB2, VBC1, VBC2 are taken from the non-ideal region of IB vs. VBE in the reverse bias mode.

CIRCUIT: use the REVERSE DC CHARACTERISTICS CIRCUIT SET-UP

EFFECT OF PARAMETER:
NC and ISC are the counterparts of NE and ISE for the reverse DC non-ideal region. NC determines the curving of IB in the non-ideal region when the transistor is reverse biased.



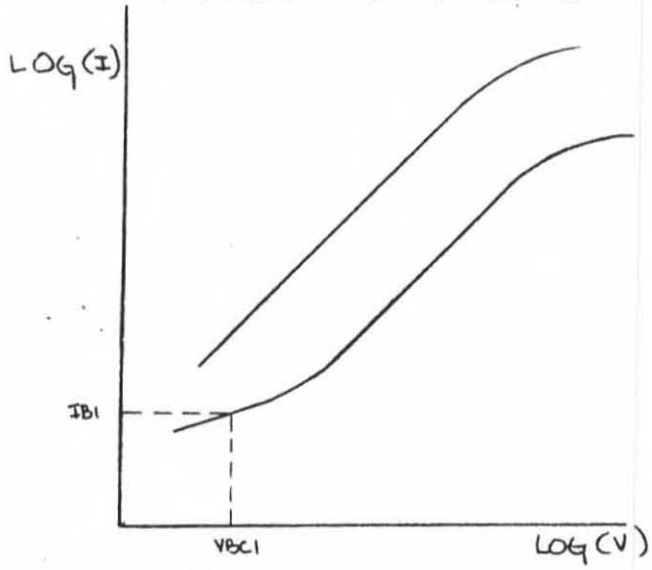
PARAMETER: ISC

DEFINITION: base-collector leakage saturation current

MEASURED VALUE: 3.55 E-9 amperes
TYPICAL VALUE: 1 E-16 amperes
SPICE DEFAULT: 0 amperes

METHOD:

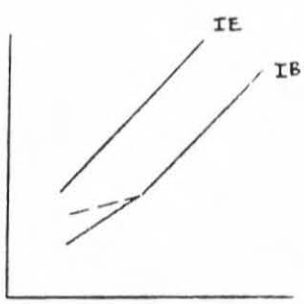
$$ISC = IB1 / [\exp(VBC1/NC(Vt))-1]$$



NOTE: 1. IB1 and VBC1 are taken from the non-ideal region of IB vs. VBC with the transistor in the reverse DC biased mode.
2. NC is needed to calculate ISC.

CIRCUIT: use the REVERSE DC CHARACTERISTICS CIRCUIT SET-UP

EFFECT OF PARAMETER:
ISC determines the slope of the non-ideal region of IB when the transistor is reverse DC biased.



PARAMETER: RB

DEFINITION: zero biased base resistance

MEASURED VALUE: 40 ohms
TYPICAL VALUE: 100 ohms
SPICE DEFAULT: 0 ohms

METHOD:

For DC analyses it is possible to obtain RB from a plot of ln(IC) and ln(IB) vs. VBE. However, since this procedure involves subtracting two large numbers, it is not uncommon to obtain negative values for RB with this method.

A. Using IS BF RE and IB IE and VBE in the ohmic region

RB = 1/IB [VBE - VT*ln(IB/IS)*BF - IE*RE) where
IE =IB+IC

B. Pulse Measurement Method

A current pulse is applied to the base and causes the device to turn off. The voltage across RB drops to zero while the base capacitance keeps the junction potential, VBE, constant. RB is then determined by:

RB = ΔVBE/Ipulse generator

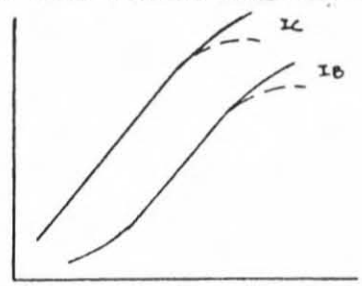
When the voltage drop no longer appears vertical on an oscilloscope trace, the constant-resistance model for RB is no longer valid. Adjusting the time base of the oscilloscope until this condition is reached gives some indication of the switching times at which the simple RB model is not adequate.

Some other techniques not mentioned here are, the noise measurement technique (for noise performance), Impedance circle method (for small-signal tests).

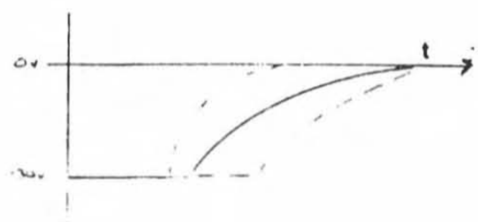
NOTE:
1. RB is one of the most difficult parameters to measure because it is modeled as a lumped constant resistance although it is actually a distributed variable resistance.
2. The value of RB obtained is strongly dependent upon the measurement technique used as well as the transistor's operating conditions.
3. Thus the application of the model should determine the test measurement technique to be used. Some other methods are the pulse measurement method, noise measurement method and the DC measurement method (See References)
4. The user may find that it is easier to "play" with the value of RB until a satisfactory model is derived rather than try and measure RB from a test method.

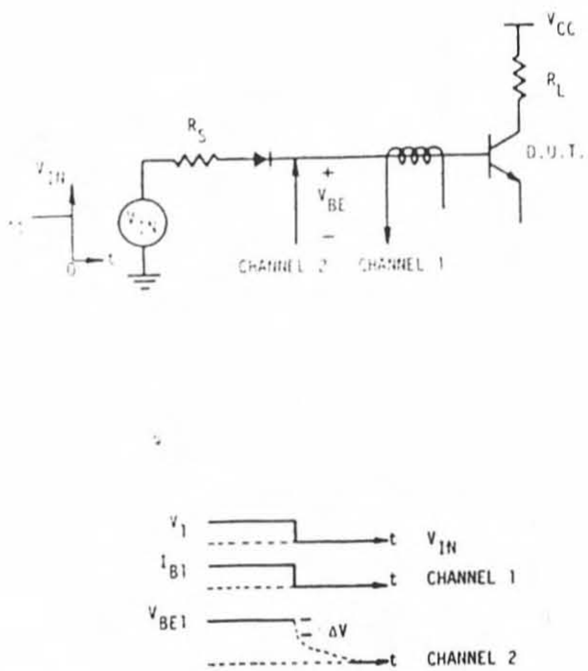
EFFECT OF PARAMETER:

RB significantly affects the ohmic region of IB, IC and IE in both the forward and reverse DC biased modes. IB is especially susceptible to changes in RB. As RB increases, the current curves in the ohmic region bend downward.



RB also affects the switching time of the transistor model. Increasing or decreasing RB changes the delay and storage times of the transistor. Base resistances greatest impact is normally its effect on the small-signal and transient responses.





Measurement Setup to Determine r_b' by the Pulse Method

PARAMETER: RE

DEFINITION: emitter parasitic resistance

MEASURED VALUE: .5 ohms
TYPICAL VALUE: 1 ohm
SPICE DEFAULT: 0 ohms

METHOD:
11. RE Emitter Resistance

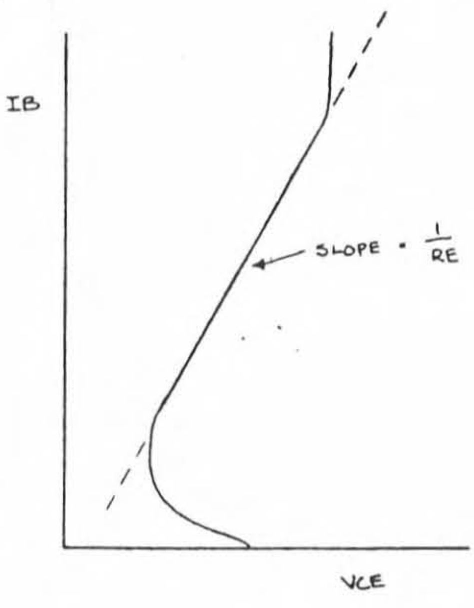
A curve tracer can be used:

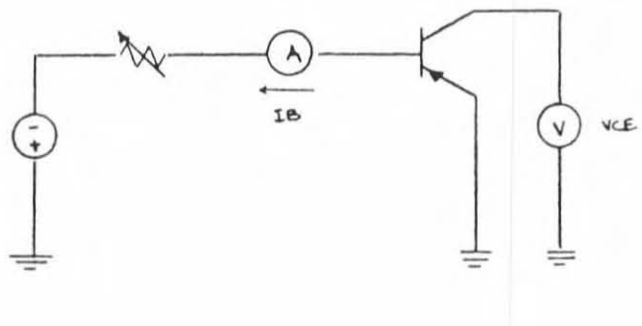
Curve Tracer Connections	Transistor Connections
Collector	Base
Base	Collector
Emitter	Emitter

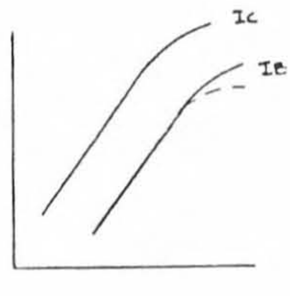
Display the IB vs. VCE characteristics. The connection switch is set to emitter grounded, base terminal open. The horizontal knob is set to read base volts (VCE) and the proper ranges are selected to yield an easily readable slope. Choose two points. The straight line portion of the curve is = 1/RE. The slope should be determined as close to the flyback portion at the bottom as possible.

$RE = \Delta VCE/\Delta IB$.

CIRCUIT DESIGN:







NOTE: 1. RE is the inverse of the slope of the straight line portion of the graph.

EFFECT OF PARAMETER:

RE mainly affects the ohmic region of IB in the forward DC biased mode. It has no significant effects on IC in the forward mode and has no noticable effects in the reverse biased mode. As RE increases IB's ohmic region concaves increasingly downward.

PARAMETER: RC

DEFINITION: collector parasitic resistance

MEASURED VALUE: 10 ohms
TYPICAL VALUE: 10 ohms
SPICE DEFAULT: 0 ohms

METHOD:
Measure IB vs. VEC, a Curve Trace can be used.

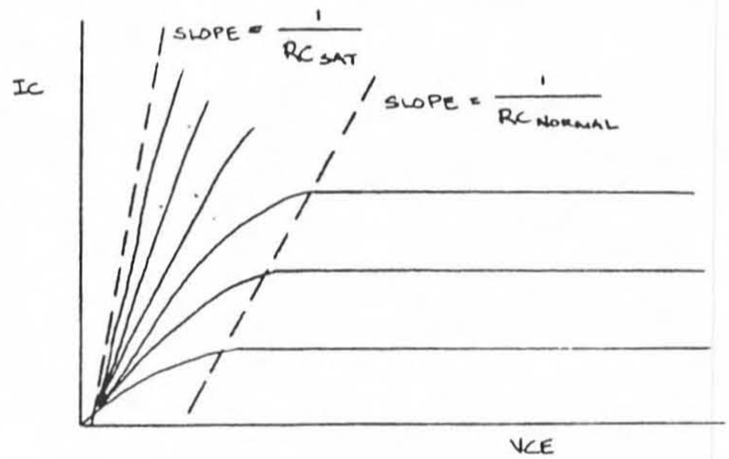
Curve Tracer Connections	Transistor Connections
Collector	Base
Base	Emitter
Emitter	Collector

RC = (VEC1-VEC2)/(IB1-IB2)

Use the same set up as for RE.

RC may be obtained from a curve tracer photograph at low values of VCE vs. IC. RCsat and RCnormal are the two limiting values of RC. The curve tracer settings are

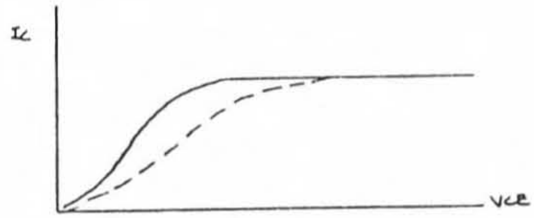
VERT - collector current		1ma/div
HORIZ - collector-emitter voltage		.2v/div
STEP - base current		



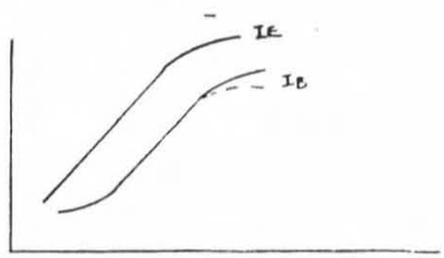
NOTE: 1. The RCnormal line is drawn through the knees of the characteristic curves.
2. RCnormal < RC < RCsat most of the time.

EFFECT OF PARAMETER:

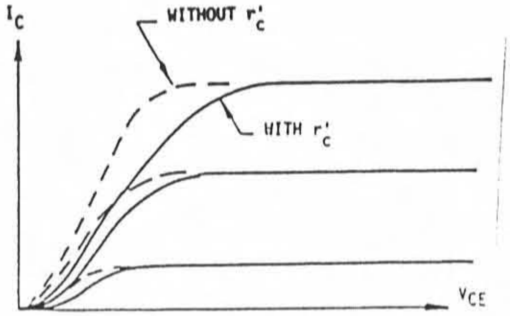
RC affects the collector trace curves by suppressing the characteristic curves at low VCE. The larger RC is, the more suppressed the curves become.



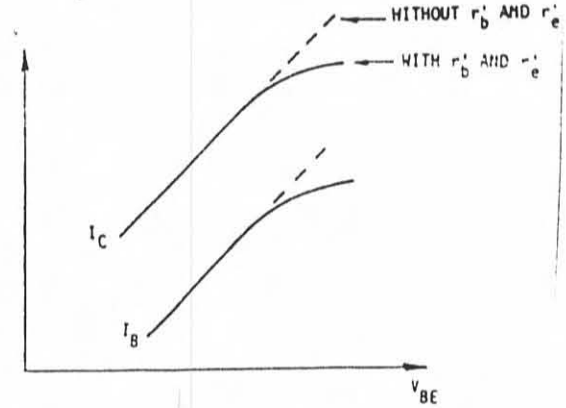
RC also strongly influences the ohmic region of IB in the reverse DC operating mode. The greater RC is, the more concaved IB becomes in the ohmic region.



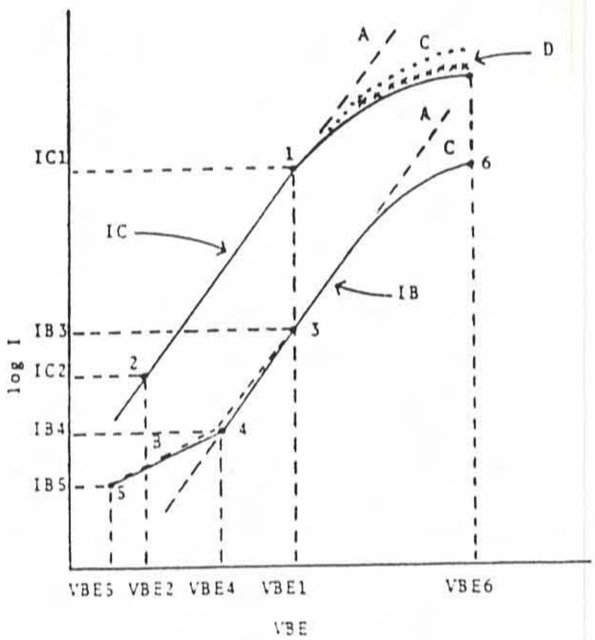
PARAMETER "TWEAKING"



Effect of r_c'



Effect of r_b' and r_e'



LEGEND:

———	Measured Data
A - - -	NF, IS, and BF specified.
B ------	NE and ISE added.
C	RE and RB added.
D xxxxxx	IKF added.

Collective Effect Of Parameters

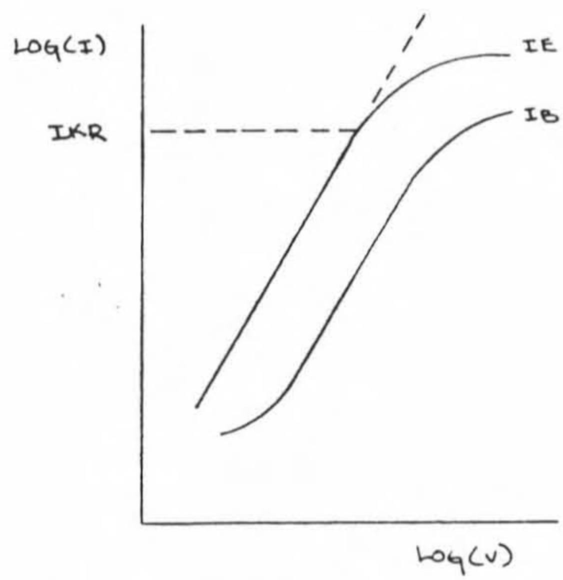
PARAMETER: IKR

DEFINITION: corner of reverse beta high current roll-off

MEASURED VALUE: 3 E-3 amperes
TYPICAL VALUE: -
SPICE DEFAULT: infinite

METHOD:

IKR is found the same way IKF is found, only now it is using reverse DC bias. IKR is the value of IE at the transition between the ideal and ohmic region for a reverse biased transistor. IKR is the value of IE where B is equal to BR/2. Again, IKR has to be found by curve fitting.



CIRCUIT: use the REVERSE DC CHARACTERISTICS CIRCUIT SET-UP

EFFECT OF PARAMETER:

IKR affects IE (in the reverse DC biased mode) in the same way that IKF affects IC (in the forward DC biased mode).

PARAMETER: IKF

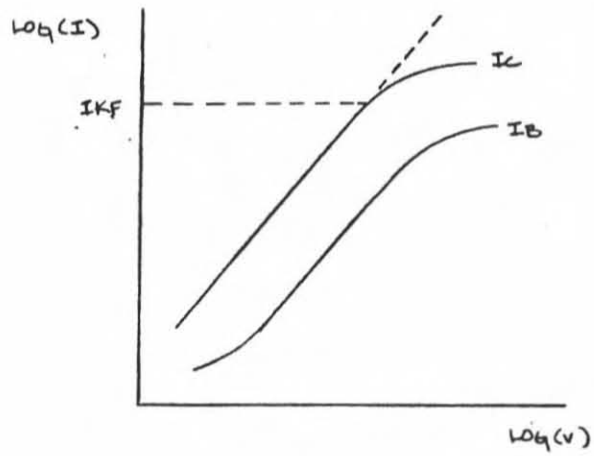
DEFINITION: corner for forward beta high current roll-off

MEASURED VALUE: 4 E-3 amps
TYPICAL VALUE: -
SPICE DEFAULT: infinite

METHOD:

IKF is not easily determined from measured data. It is the value of IC at the transition between the ideal and ohmic region.

The method used to find IKF was to choose a value for IKF and check the model fit of IC vs. VBE. If the SPICE model and actual measurements did not corrolate then another value was chosen.

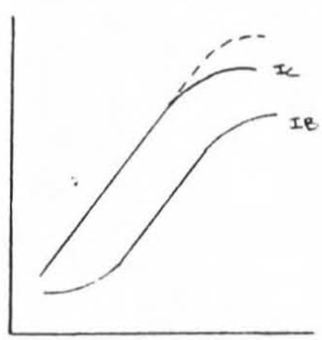


NOTE: 1. IKF is also equal to the value of the collector current at the point where BF is 1/2 of its maximum value (BF/2).
2. "Curve fitting" is the only easy way to find IKF.

CIRCUIT: use the FORWARD DC CHARACTERISTICS CIRCUIT SET-UP

EFFECT OF PARAMETER:

IKF affects the ohmic region of IC in the forward biased DC curves.



IKF also has some effects on the switching time of the transistor.

PARAMETER: VAF

DEFINITION: forward early voltage

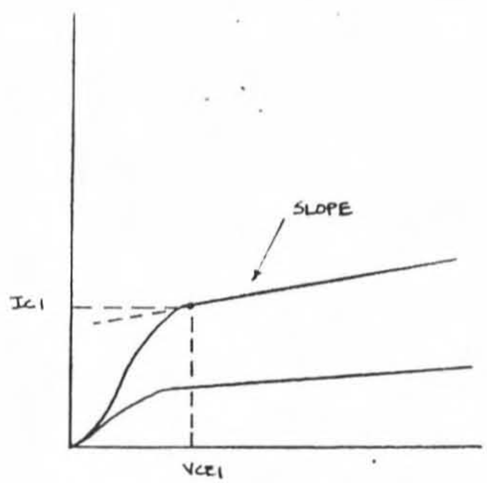
MEASURED VALUE: 48.2 volts
TYPICAL VALUE: 100 volts
SPICE DEFAULT: infinite

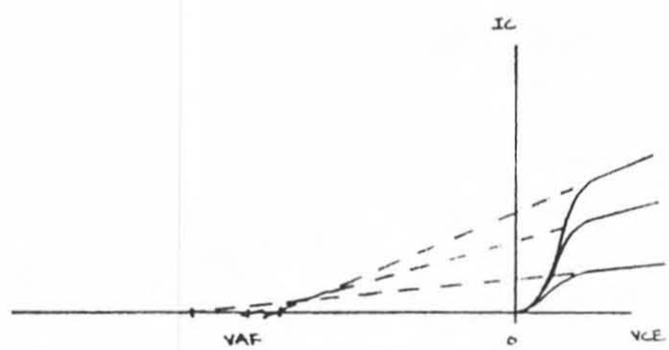
METHOD:

A curve tracer photograph is used to find VAF. VAf is the negetive of the extrapolated intercepts of IC vs. VCE on the VCE axis. The curve tracer settings were,

VERT	- collector current	.5mA/div
HORIZ	- collector-emitter voltage	.2V/div
STEP	- base current	5uA/div

VAF = IC1/slope - VCE1

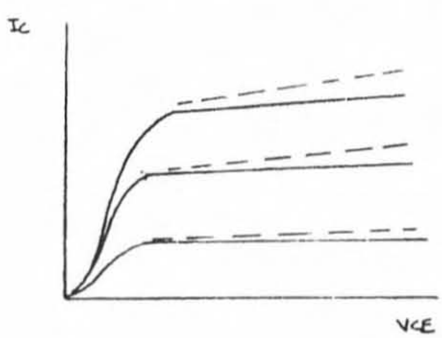




NOTE: 1. When extrapolations spread over a range of values, use an average or geometric mean of the value for VAF.

EFFECT OF PARAMETER:

VAF affects the slope of the linear segments of the collector characteristic curves. The smaller VAF is, the larger the slope.



PARAMETER: VAR

DEFINITION: reverse early voltage

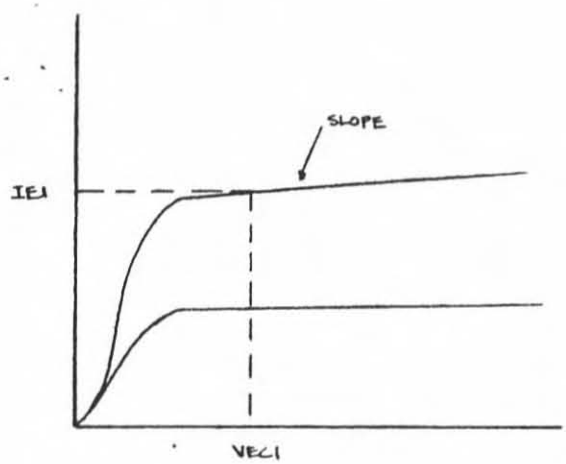
MEASURED VALUE: 7.3 volts
TYPICAL VALUE: 10 volts
SPICE DEFAULT: infinite

METHOD:

VAR is found the same way as VAF. The only difference is the collector and emitter pins are exchanged when interfacing the transistor with the curve tracer. The settings are,

VERT	- collector current (actually IE)	20uA/div
HORIZ	- collector-emitter voltage (actually VEC)	.2v/div
STEP	- base current	5uA/div

$$VAR = IE1/slope - VEC1$$



EFFECT OF PARAMETER:

VAR affects the slope of the linear segments of the emitter characteristic curves. The smaller VAR is, the larger the slope.

PARAMETER: CJE

DEFINITION: base-emitter zero-biased depletion capacitance

MEASURED VALUE: 23.0 E-12 farads
TYPICAL VALUE: 10.0 E-12 farads
SPICE DEFAULT: 0 farads

METHOD:
CJE was obtained using a multifrequency LCR meter. Using no external biasing, the junction capacitance between the base and the emitter was measured. The collector terminal was kept open.

EFFECT OF PARAMETER:
CJE mainly affects the frequency response as well as the switching time of the transistor.

NOTE:
CJE, MJE, VJE are all parameters relating to the emitter junction capacitance by the equation,

CEdepletion = CJE / [(1-VBE/VJE)**MJE]

where,
CEdepletion = base-emitter junction depletion capacitance
VBE = reverse biased base-emitter voltage
and,
** = "raised to the power of"

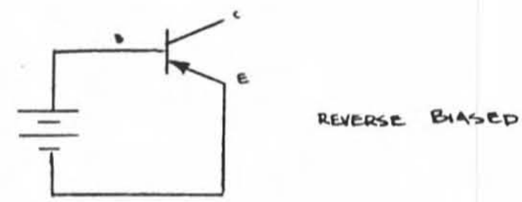
PARAMETER: VJE

DEFINITION: base-emitter built-in potential

MEASURED VALUE: 0.85 volts
TYPICAL VALUE: 0.6 volts
SPICE DEFAULT: 0.75 volts

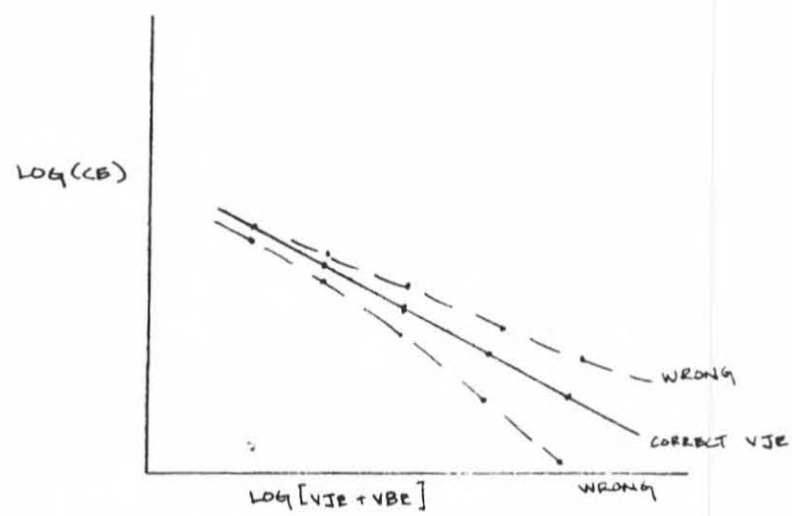
METHOD:

VJE can be obtained from measurements of the base to emitter junction capacitance (CE) vs. the reverse biased base to emitter voltage (VBE). A multifrequency LCR meter with external biasing was used to measure CE vs. VBE. During the measurement the collector terminal is left open.



A graphical method is then used.

1. Tabulate CE vs. VBEreverse-biased
2. Assume a value for VJE (usually between 0.6v and 1.0v)
3. Tabulate [VJE+VBEreverse]
4. Plot CE vs.[VJE+VBEreverse] on log-log graph paper
5. IF the line is straight then the assumed VJE is correct
6. IF the line is not straight, go back to step 2 and assume another value for VJE



EFFECT OF PARAMETER:

VJE affects the frequency response and switching time of the transistor.

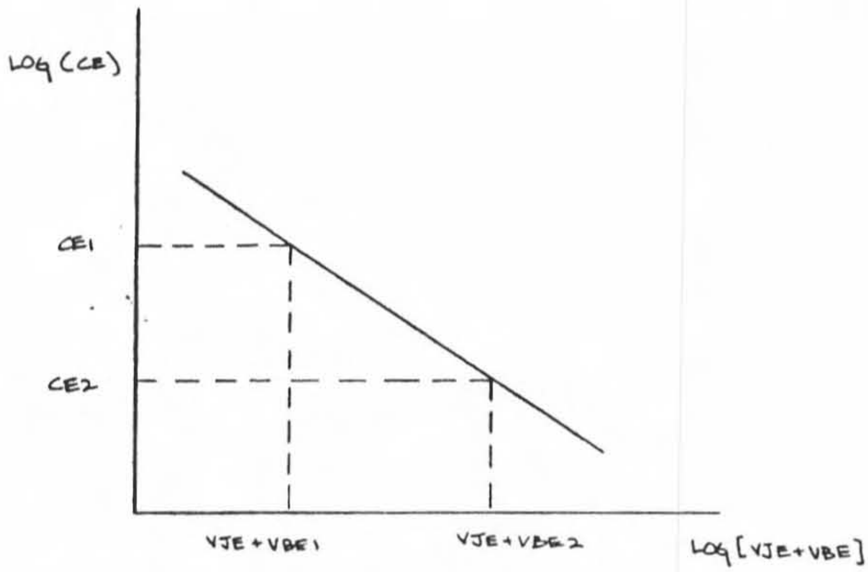
PARAMETER: MJE

DEFINITION: base-emitter junction exponentioal factor

MEASURED VALUE: 0.4
TYPICAL VALUE: 0.5
SPICE DEFAULT: 0.33

METHOD:

-MJE = [LN(CE1)-LN(CE2)] / [LN(VJE+VBE1)-LN(VJE+VBE2)]



NOTE: 1. The straight line of CE vs. (VJE+VBE) must first be found in order to obtain MJE.

EFFECT OF PARAMETER:
MJE affects the frequency response and switching time of the transistor model.

PARAMETER: CJC

DEFINITION: **base-collector zero-bias depletion capacitance**

MEASURED VALUE: **19.4 E-12 farads**
TYPICAL VALUE: **10 E-12 farads**
SPICE DEFAULT: **0 farads**

METHOD:
CJC was obtained with a multifrequency LCR meter. Using no external biasing, the junction capacitance between the base and the collector was measured. The emitter was left open.

EFFECT OF PARAMETER:
CJC affects the frequency response and switching times of the transistor model.

NOTE:
CJC, MJC, VJC are all parameters relating to the base-collector junction capacitance by the equation,

CCdepletion = CJC / [(1-VBC/VJC)**MJC]

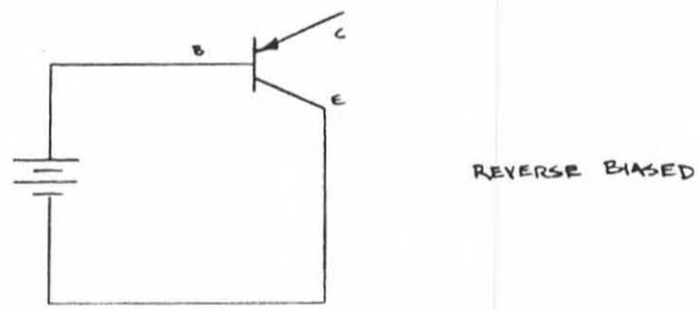
where,
CCdepletion = base-collector junction depletion capacitance
VBE = reverse biased base-collector voltage
and,
** = "raised to the power of"

PARAMETER: VJC

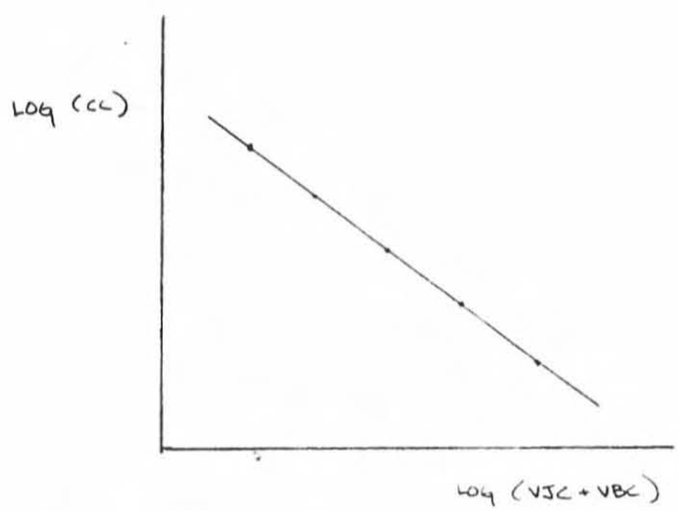
DEFINITION: base-collector built-in potential

MEASURED VALUE: 0.5 volts
TYPICAL VALUE: 0.6 volts
SPICE DEFAULT: 0.75 volts

METHOD:
VJC can be obtained in the same manner as VJE. Using a multifrequency LCR meter with external biasing, the base-collector junction capacitance (CC) vs. the reverse base-collector voltage (VBC) was measured.



Again, the graphical method was used to find VJC.



EFFECT OF PARAMETER:
VJC affects the frequency response and switching time of the transistor model.

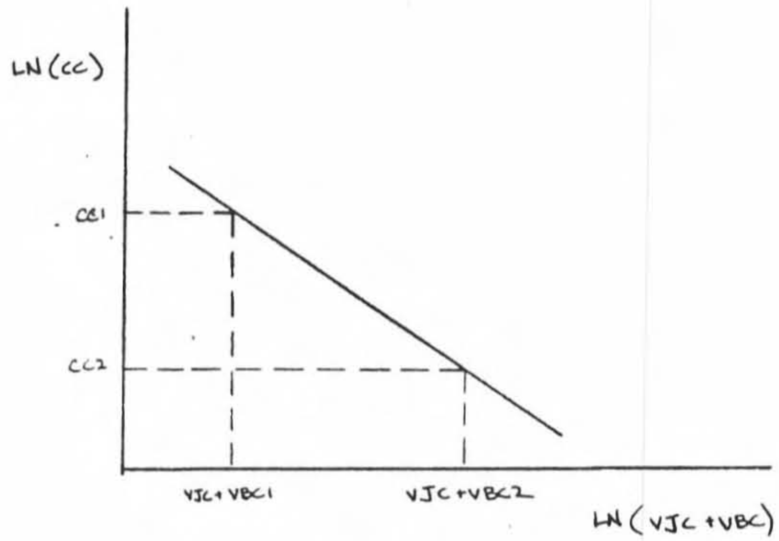
PARAMETER: MJC

DEFINITION: base-collector junction exponential factor

MEASURED VALUE: 0.4
TYPICAL VALUE: 0.5
SPICE DEFAULT: 0.33

METHOD:

-MJC = [LN(CC1)-LN(CC2)] / [LN(VJC+VBC1)-LN(VJC+VBC2)]



NOTE: 1. A straight line of CC vs. (VJC+VBC) must first be found in order to obtain MJC.

EFFECT OF PARAMETER:
MJC affects the frequency response and switching time of the transistor model.

PARAMETER: TF

DEFINITION: ideal forward transit time

MEASURED VALUE: 5.2 E-10 seconds
TYPICAL VALUE: 10 E-10 seconds
SPICE DEFAULT: 0 seconds

METHOD:

TF = 1/[2(pi)(Ft)] - (CC)(RC)

Ft = 1 / [(1/Fmeas)-2(pi)(CC)(Rcollector)] for Rcollector >> 0

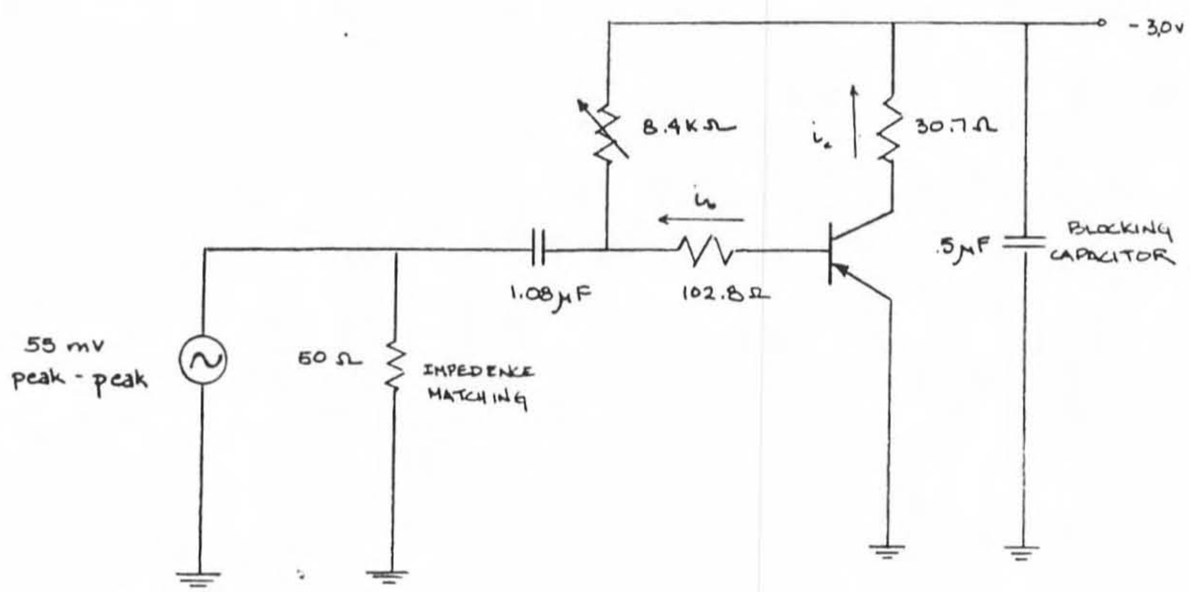
Fmeas = (Fbeta)(Bo)

where,

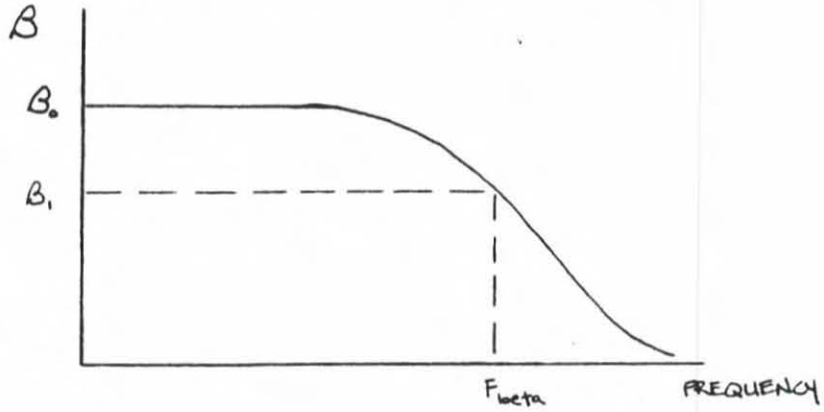
Fbeta = frequency at which the magnitude of beta is 1/sqrt[Bo]
Bo = low frequency beta
Ft = unity gain frequency

NOTE: 1. CC is the base-collector junction depletion capacitance biased at the same VCB as the circuit operating point.
2. Rcollector is the resistor on the collector lead of the circuit.

This method determines Ft from the frequency response of the transistor in order to obtain TF. Using the following circuit set-up, a frequency response is plotted (AC beta vs. frequency).



From the frequency response, Fmeas is found.



$$\beta_1 = \frac{\beta_0}{\sqrt{2}} \qquad F_{beta} = F @ \beta = \beta_1 \qquad F_{meas} = (F_{beta})(\beta_0)$$

And finally TF is found.

NOTE: 1. Beta is the AC gain of the transistor and not the DC gain.

EFFECT OF PARAMETER:
TF affects the frequency response and switching time of the transistor model.

PARAMETER: TR

DEFINITION: ideal reverse transit time

MEASURED VALUE: 34.4 E-9 seconds
TYPICAL VALUE: 10 E-9 seconds
SPICE DEFAULT: 0 seconds

METHOD:

TR was found in the same way as TF. The only difference was the collector and emitter leads were interchanged when finding the frequency response.

TR = 1/[2(pi)(Ft)] - (CE)(RE)

Ft = 1 / [(1/Fmeas)-2(pi)(CE)(Remitter)] for Remitter >> 0

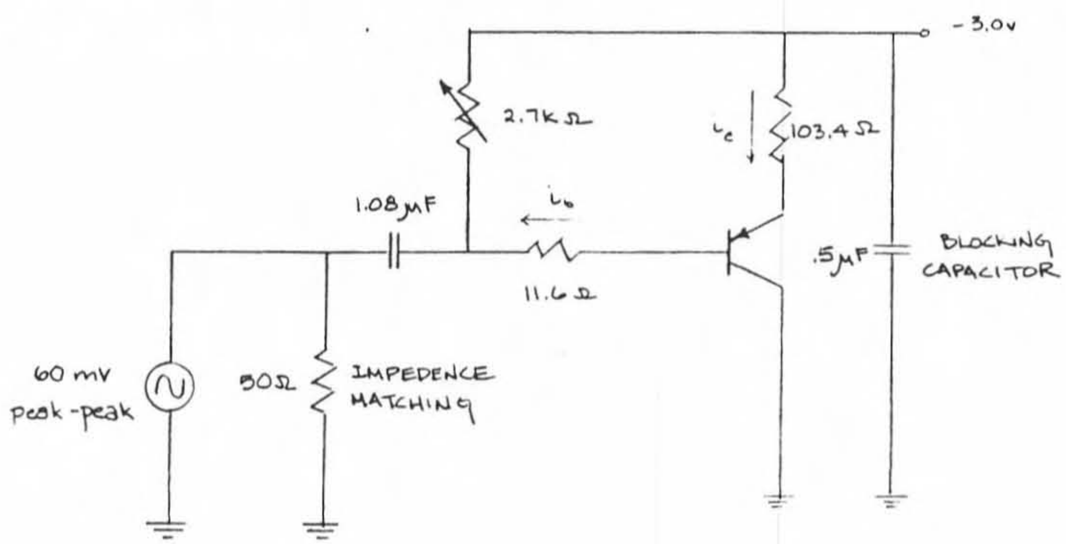
Fmeas = (Fbeta)(Bo)

where,

Fbeta = frequency at which the magnitude of beta is 1/sqrt(2) of Bo
Bo = low frequency beta
Ft = unity gain frequency

NOTE: 1. CE is the base-emitter junction depletion capacitance biased at the same VCE as the circuit operating point.
2. Remitter is the resistor on the emitter lead of the circuit.

The test circuit used to find Ft is,



EFFECT OF PARAMETER:

TR affects the frequency response and switching time of the transistor model.

SUMMARY:

SUMMARY OF SPICE PARAMETER VALUES FOR THE 2N2907A PNP BJT TRANSISTOR

[parameter]	[value]	[default]	[note]
NF	1.21	1.0	
IS	1.10 E-12 amps	1 E-16 amps	
BF	202	100	
EG	1.1 e-volts	1.1 e-volts	use default
BR	11	1	
NR	1.04	1	use default
NE	1.92	1.5	
ISE	6.67 E-12 amps	0 amps	
NC	4.48	2	
ISC	3.55 E-9 amps	0 amps	
RB	40 ohms	0 ohms	
RE	0.5 ohms	0 ohms	
RC	10 ohms	0 ohms	
IKF	4 E-3 amps	infinite	
IKR	3 E-3 amps	infinite	
VAF	48.2 volts	infinite	
VAR	7.3 volts	infinite	
CJE	23.0 E-12 farads	0 farads	
VJE	0.85 volts	0.75 volts	
MJE	0.4	0.33	
CJC	19.4 E-12 farads	0 farads	
VJC	0.5 volts	0.75 volts	
MJC	0.4	0.33	
TF	5.2 E-10 seconds	0 seconds	
TR	34.4 E-9 seconds	0 seconds	

EXAMPLE:

ACTUAL TEST OF 2N2907 PNP TRANSISTOR

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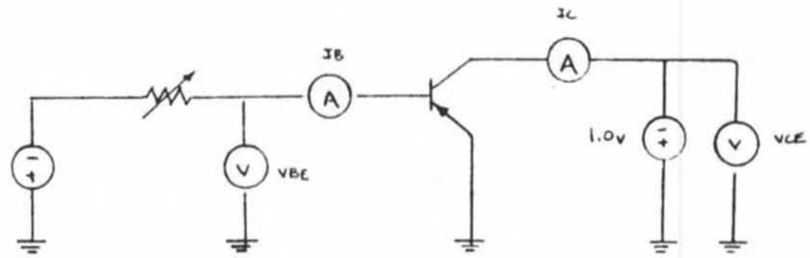
PAGE ______

EXAMPLE: FORWARD DC CHARACTERISTICS



VBE	IB	IC
.425 v	.035 μA	.002 mA
.450 v	.057 μA	.004 mA
.475 v	.094 μA	.008 mA
.500 v	.153 μA	.015 mA
.525 v	.257 μA	.024 mA
.550 v	.413 μA	.047 mA
.575 v	.733 μA	.092 mA
.600 v	1.463 μA	.201 mA
.625 v	3.140 μA	.476 mA
.650 v	6.647 μA	1.09 mA
.675 v	12.97 μA	2.23 mA
.700 v	22.82 μA	4.02 mA
.725 v	36.05 μA	6.46 mA
.750 v	51.68 μA	9.29 mA
.775 v	69.37 μA	12.48 mA
.800 v	88.29 μA	15.84 mA
.825 v	108.9 μA	19.46 mA
.850 v	130.6 μA	23.62 mA
.875 v	153.1 μA	27.33 mA
.900 v	175.4 μA	31.11 mA
.925 v	198.7 μA	35.05 mA
.950 v		38.79 mA
.975 v		43.73 mA
1.000 v		46.17 mA
1.025 v		49.83 mA
1.050 v		53.32 mA

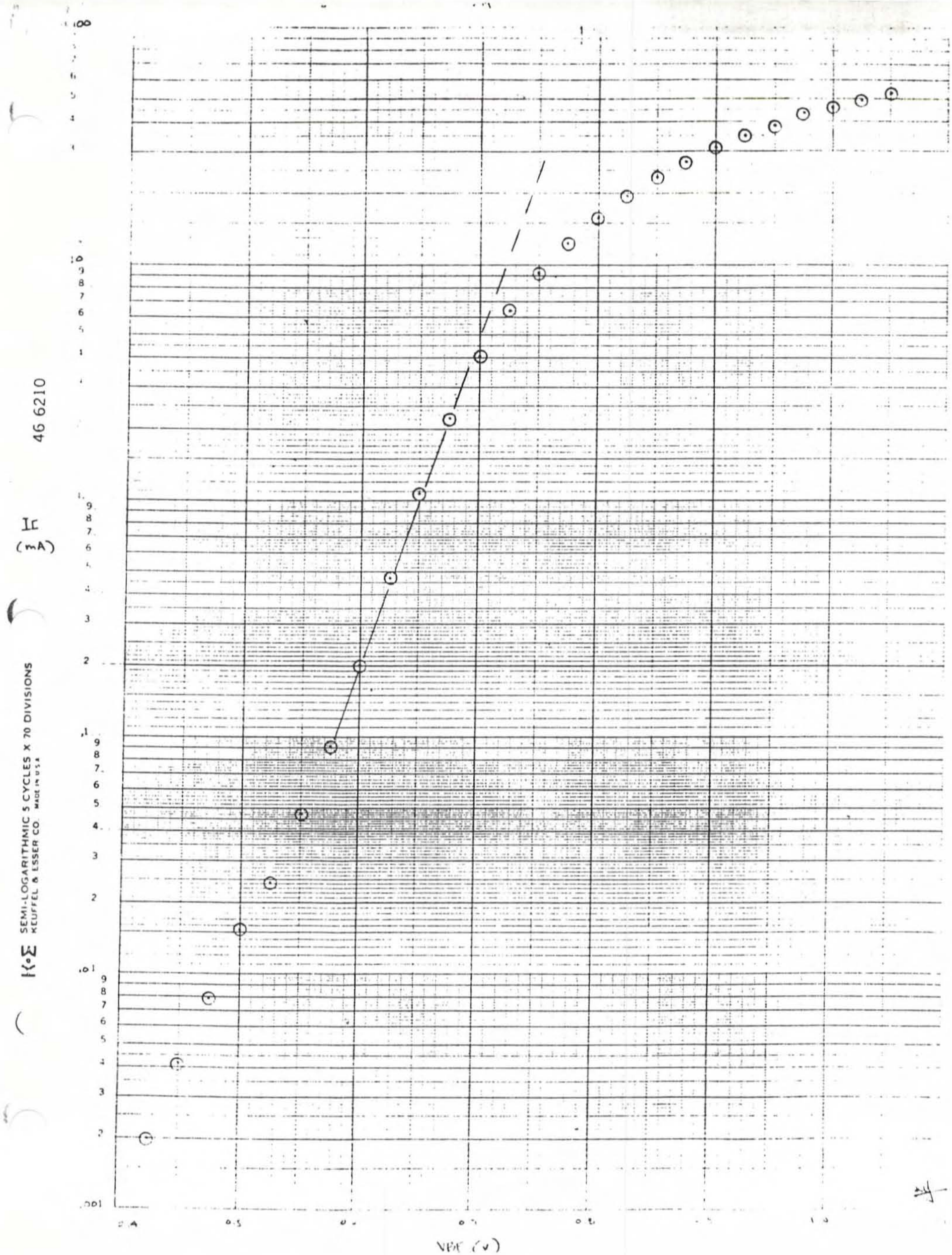
$$NF = \frac{.675 - .575}{(.026)\ LN\left(2.225/.0915\right)} = 1.21$$

$$IS = \frac{1.087 \times 10^{-3}}{EXP\left[\frac{.650}{(1.205)(.026)}\right] - 1} = 1.062 \times 10^{-12} \text{ AMPS}$$

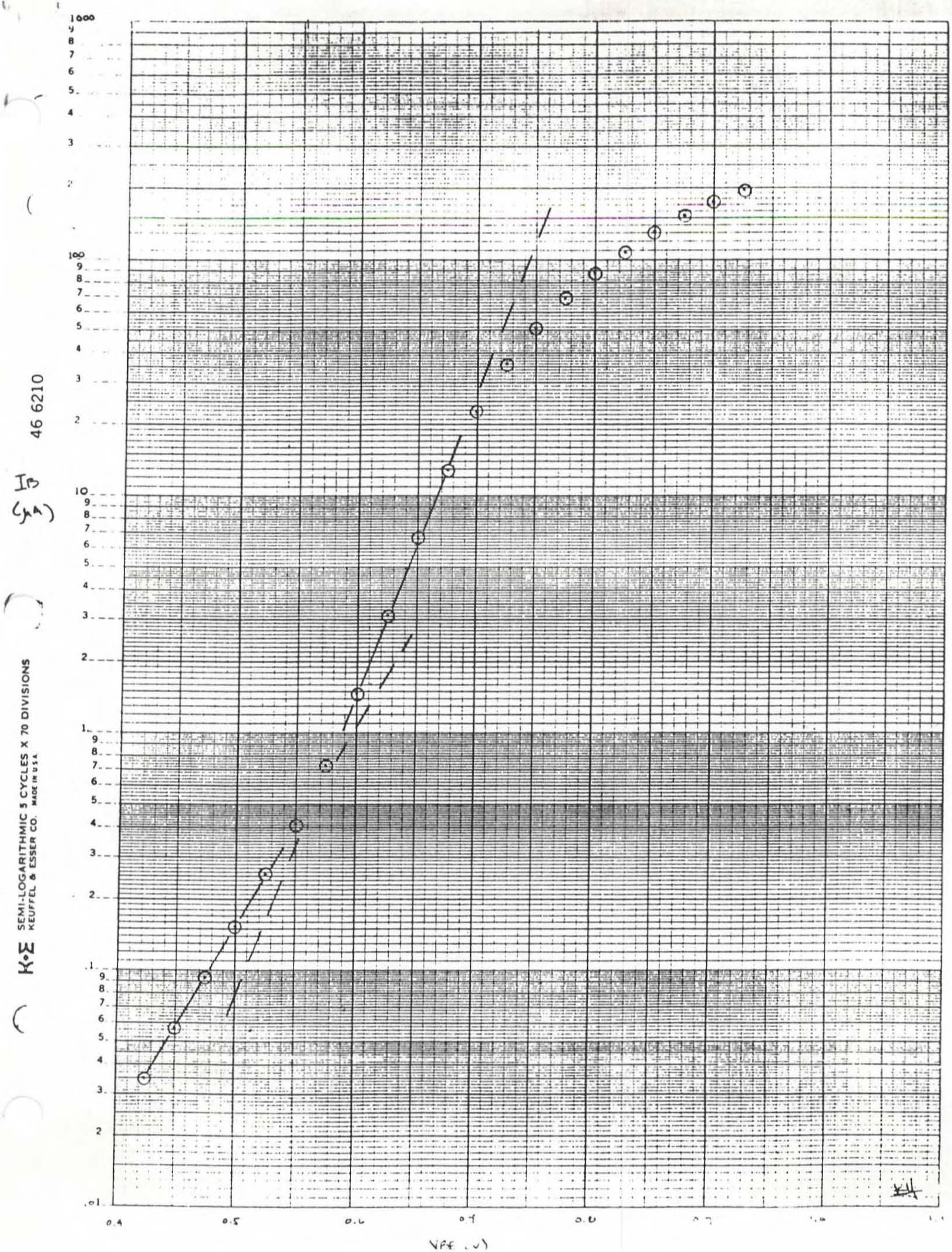
$$NE = \frac{.525 - .450}{(.026)\ LN\left(.257/.067\right)} = 1.915$$

$$ISE = \frac{.153 \times 10^{-6}}{EXP\left[\frac{.500}{(1.915)(.026)}\right] - 1} = 6.673 \times 10^{-12} \text{ AMPS}$$

$$IKF = 4 \times 10^{-3} \text{ AMPS}$$

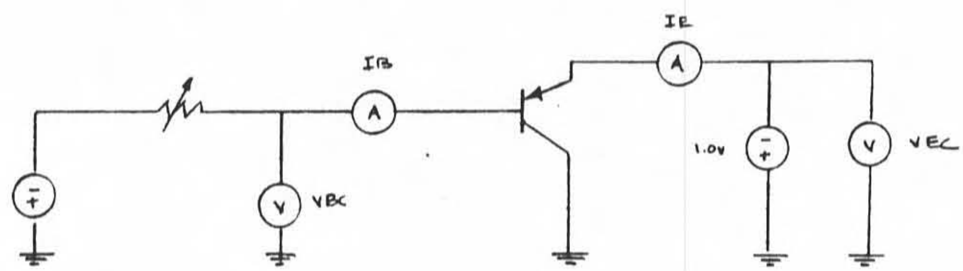


46 6210
K&E SEMI-LOGARITHMIC 5 CYCLES X 70 DIVISIONS
KEUFFEL & ESSER CO. MADE IN U.S.A.
Ic (mA)
VBE (V)



IB (μA)
VBE (V)
K•E SEMI-LOGARITHMIC 5 CYCLES X 70 DIVISIONS
KEUFFEL & ESSER CO. MADE IN U.S.A.
46 6210

EXAMPLE : REVERSE DC CHARACTERISTICS



VBC	IB	IE
.250	.028 μA	
.275	.034 μA	
.300	.043 μA	
.325	.055 μA	
.350	.077 μA	.0001 mA
.375	.110 μA	.0002 mA
.400	.170 μA	.0004 mA
.425	.267 μA	.0007 mA
.450	.423 μA	.0011 mA
.475	.743 μA	.0022 mA
.500	1.56 μA	.0049 mA
.525	3.54 μA	.012 mA
.550	7.99 μA	.031 mA
.575	17.44 μA	.079 mA
.600	37.16 μA	.212 mA
.625	77.0 μA	.526 mA
.650	158.5 μA	1.28 mA
.675	318.5 μA	2.92 mA
.700	629.5 μA	6.19 mA
.725	1.218 mA	11.94 mA
.750	2.40 mA	22.11 mA
.775	4.48 mA	35.83 mA
.800	8.07 mA	54.38 mA
.825	14.07 mA	77.78 mA
.850	23.65 mA	99.33 mA

EH

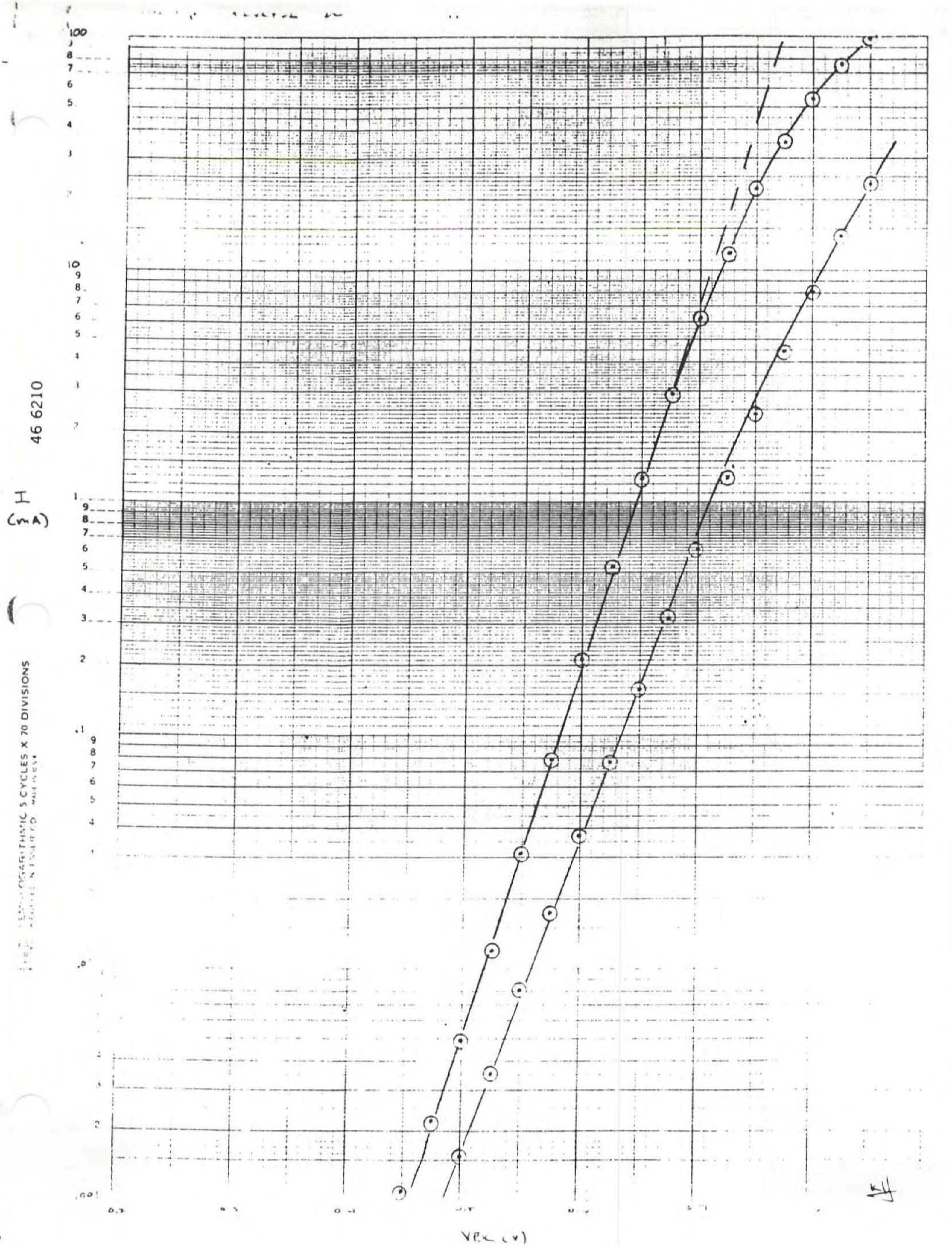
$$NR = \frac{.650 - .500}{(.026)\ LN\ (1.28/.0049)} = 1.037$$

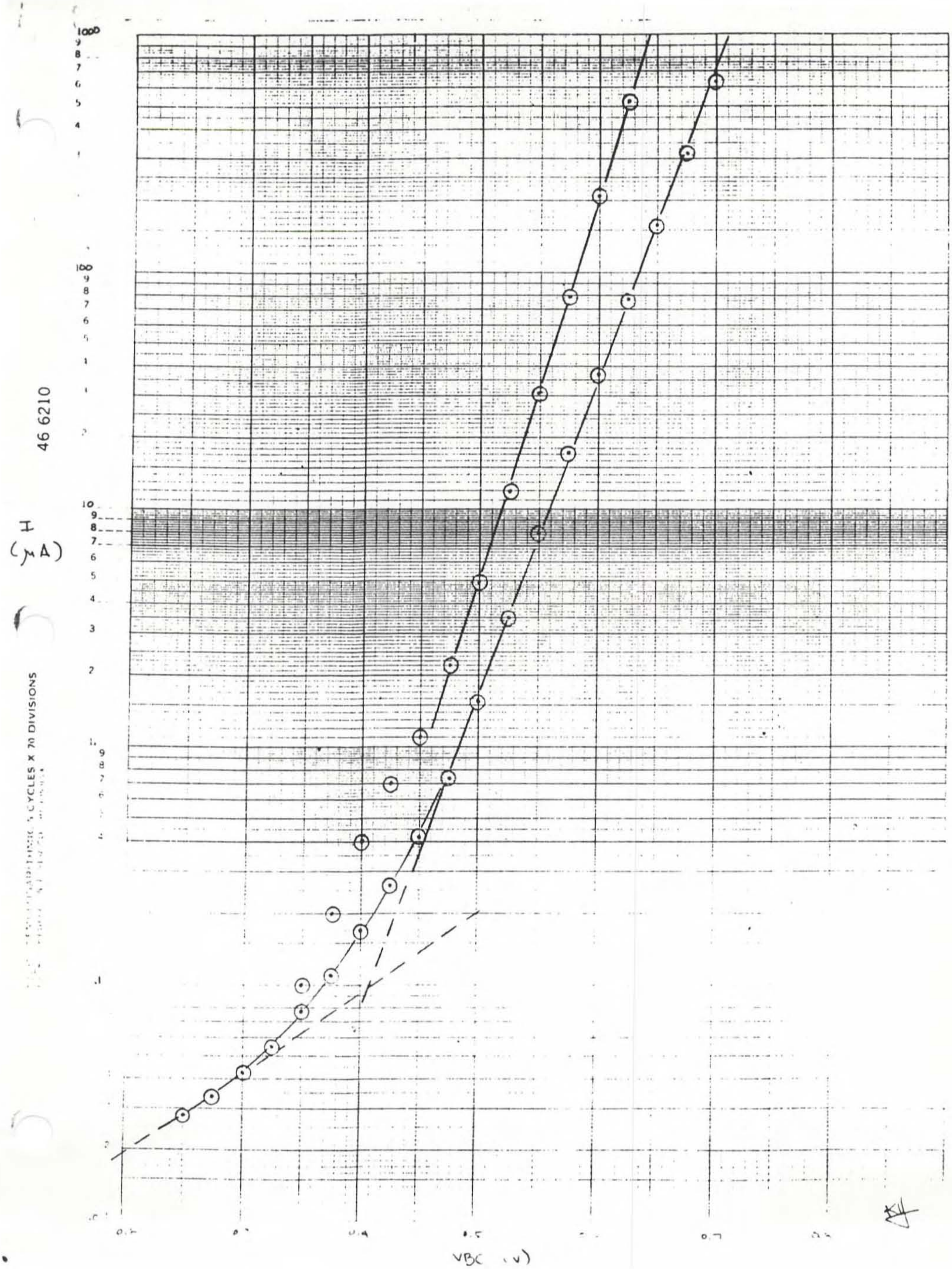
$$NC = \frac{.300 - .250}{(.026)\ LN\ (.043/.028)} = 4.483$$

$$ISC = \frac{.034 \times 10^{-6}}{EXP\left[\frac{.275}{(.026)(4.483)}\right] - 1} = 3.548 \times 10^{-9} \text{ AMPS}$$

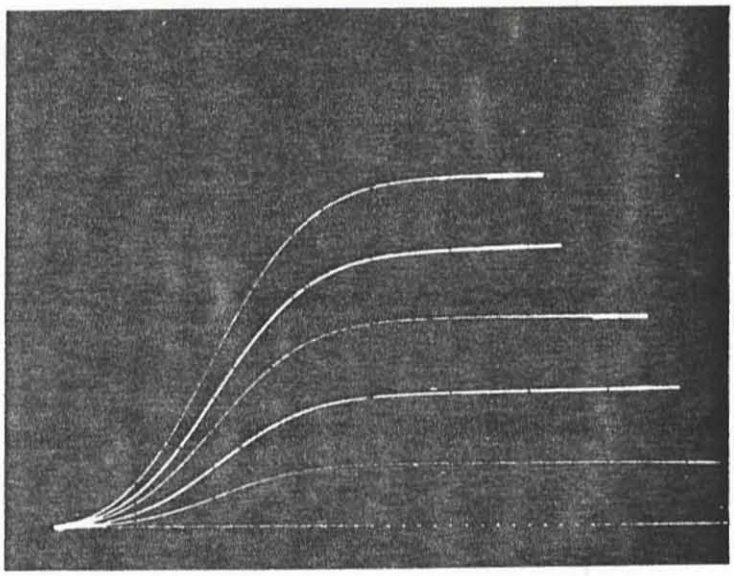
$IKR = 3 \times 10^{-3}$ AMPS

SH


100
10
1
.1
.001
46 6210
5 CYCLES X 70 DIVISIONS



1000
100
10
I
(μA)
0.4
0.5
0.7
VBC (v)
46 6210
CYCLES x 70 DIVISIONS



HORIZ 0.5 V/DIV
VERT 1 mA/DIV
STEP 5 µA/DIV

EXAMPLE: COLLECTOR TRACER CURVES TEST

$BF = \frac{6.1\ mA}{30\ \mu A} = 203$ $\quad IC = 5\ mA \quad VCE = 10V$

$BR = \frac{1.05\ mA}{10\ \mu A} = 10.5$ $\quad IE = 1\ mA \quad VEC = 5V$

RC is between RC_{SAT} and RC_{normal}

$RC_{SAT} = \frac{40\ mV}{2.4\ mA} = 16.67\ \Omega$ $\quad \therefore RC = 10\ \Omega$

$RC_{NORMAL} = \frac{0.5\ V}{5.3\ mA} = 9.4\ \Omega$

$VAF = \frac{4.40\ mA}{.09\ mA/1V} - .4V = 48.4V$ $\quad IB = 25\ \mu A$

$VAR = \frac{115\ \mu A}{12\ \mu A/.8V} - .4V = 7.3V$ $\quad IB = 25\ \mu A$

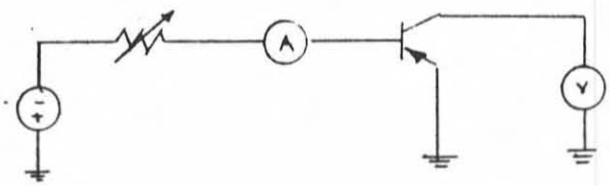
EXAMPLE :

RB from spec sheets

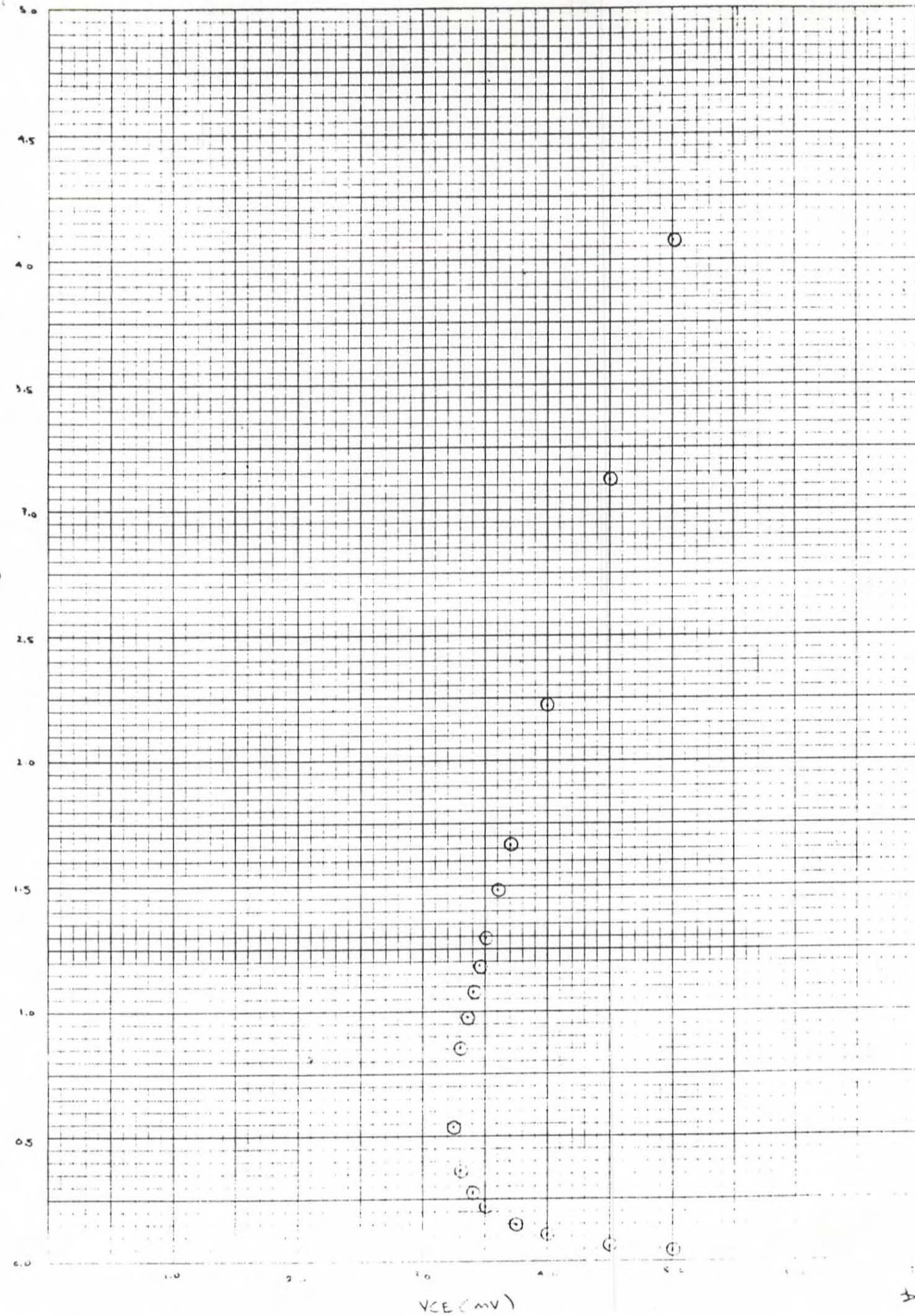
$$RB = \frac{2.6v - .6v}{50mA} = 40.0\Omega \qquad IC = 500mA \qquad IB = 50mA$$

EXAMPLE:

RE



VBE	IB
- 5.00 v	.04 mA
- 4.50 v	.062 mA
- 4.00 v	.107 mA
- 3.75 v	.149 mA
- 3.50 v	.222 mA
- 3.40 v	.274 mA
- 3.30 v	.360 mA
- 3.24 v	.540 mA
- 3.30 v	.857 mA
- 3.35 v	.980 mA
- 3.40 v	1.084 mA
- 3.45 v	1.191 mA
- 3.50 v	1.298 mA
- 3.60 v	1.480 mA
- 3.70 v	1.661 mA
- 4.00 v	2.219 mA
- 4.50 v	3.126 mA
- 5.00 v	4.076 mA



5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
IB (mA)
VCE (mV)

EXAMPLE : RLC METER MEASUREMENT

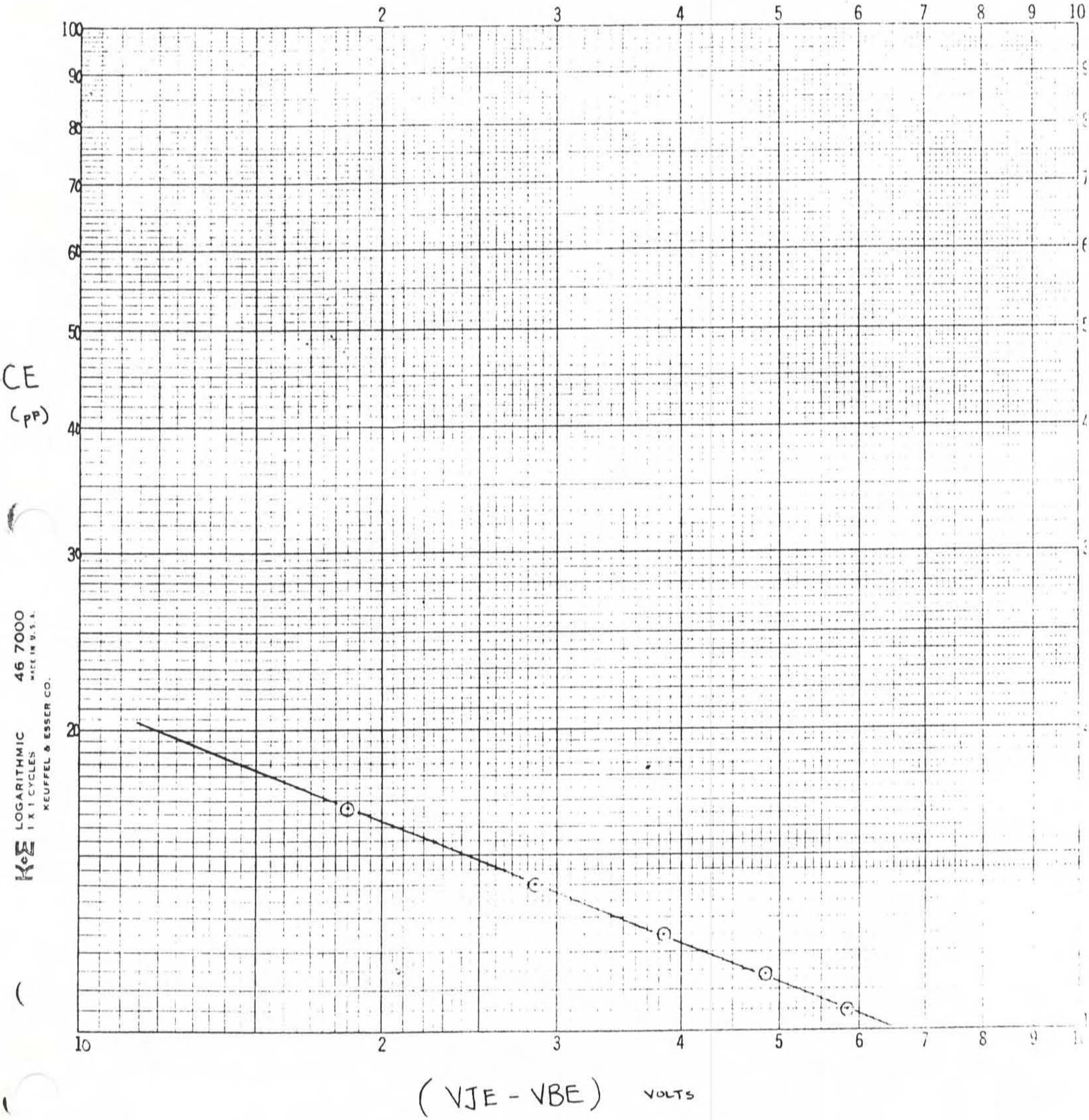
VBE	CE
0 v	23.0 pF
- 1 v	16.7 pF
- 2 v	14.0 pF
- 3 v	12.5 pF
- 4 v	11.4 pF
- 5 v	10.5 pF

$CJE = 23.0 \times 10^{-12}$ F

$VJE = .85$ v

VJE + VBE	CE
- 0.85	23 pF
- 1.85	16.7 pF
- 2.85	14.0 pF
- 3.85	12.5 pF
- 4.85	11.4 pF
- 5.85	10.5 pF

$$MJE = \frac{\ln(16.7 \times 10^{-12}) - \ln(11.4 \times 10^{-12})}{\ln(1.85) - \ln(4.85)} = 0.396$$



CE
(pF)
(VJE - VBE) VOLTS
K&E LOGARITHMIC
1 X 1 CYCLES
KEUFFEL & ESSER CO.
46 7000
MADE IN U.S.A.

VJE = -0.35V

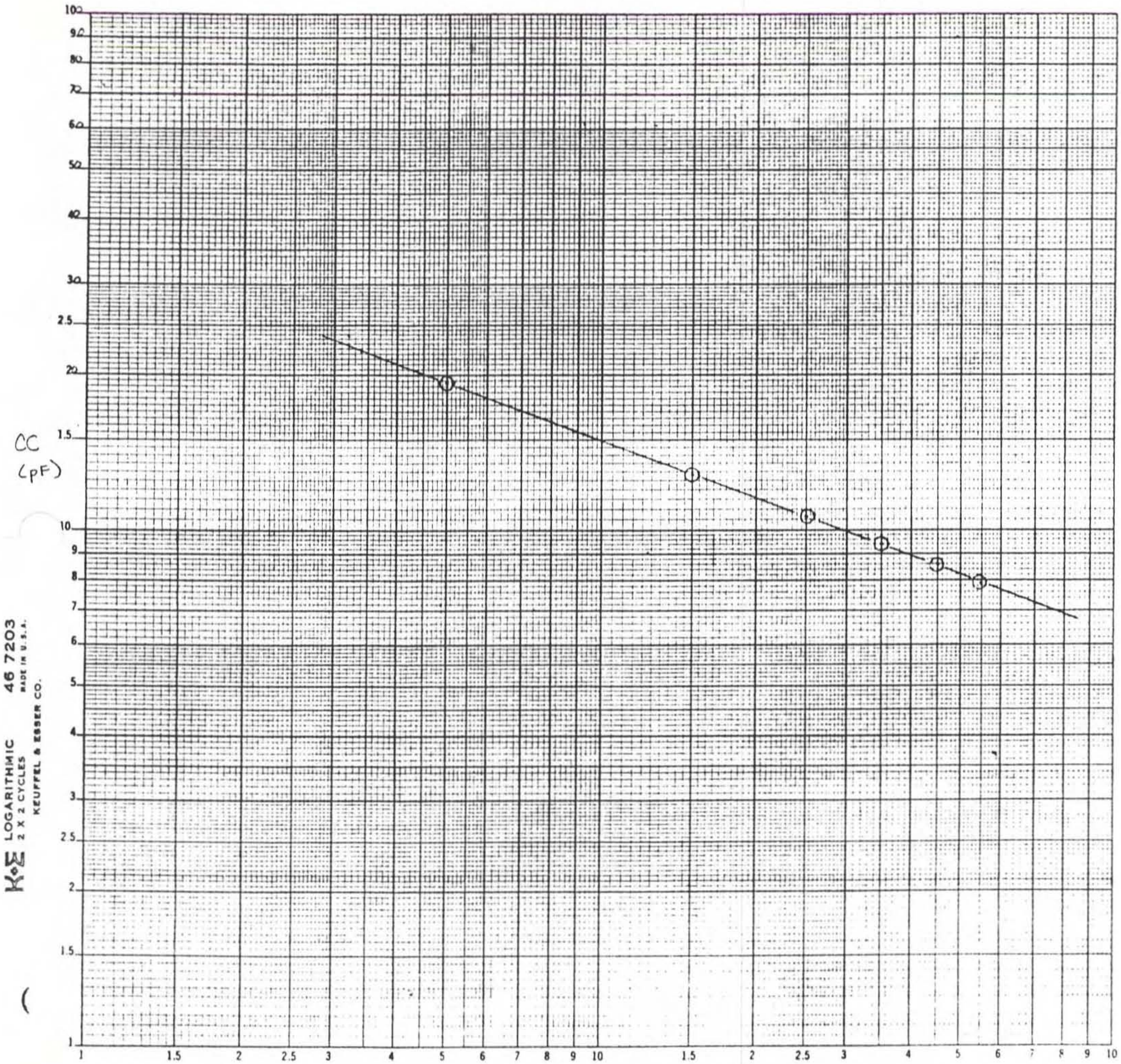
VBC	CC
0 v	19.4 pF
1 v	12.8 pF
2 v	10.6 pF
3 v	9.4 pF
4 v	8.6 pF
5 v	7.9 pF

$CJC = 19.4 \times 10^{-12}$ F

$VJC = 0.5$

(VJC + VBC)	CC
0.5	19.4 pF
1.5	12.8 pF
2.5	10.6 pF
3.5	9.4 pF
4.5	8.6 pF
5.5	7.9 pF

$$MJC = \frac{\ln(12.8 \times 10^{-12}) - \ln(8.6 \times 10^{-12})}{\ln(1.5) - \ln(4.5)} = 0.362$$


100
90
80
70
60
50
40
30
25
20
15
10
9
8
7
6
5
4
3
2.5
2
1.5
1
CC
(pF)
1
1.5
2
2.5
3
4
5
6
7
8
9
10
1.5
2
2.5
3
4
5
6
7
8
9
10
K&E LOGARITHMIC 46 7203
2 X 2 CYCLES MADE IN U.S.A.
KEUFFEL & ESSER CO.

(VJC - VBC)

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PAGE

EXAMPLE : TF

FREQ	I_b	I_c	β_{AC}
50K Hz	22.5mV/102.8Ω	1v/30.7Ω	148.8
70K Hz	22.5mV/102.8Ω	1v/30.7Ω	148.8
100K Hz	22.5mV/102.8Ω	1v/30.7Ω	148.8
300K Hz	22.5mV/102.8Ω	.985v/30.7Ω	146.6
500K Hz	22.5mV/102.8Ω	.910v/30.7Ω	135.4
700K Hz	22.5mV/102.8Ω	.860v/30.7Ω	128.0
1M Hz	25mV/102.8Ω	.790v/30.7Ω	105.8
1.5M Hz	27.5mV/102.8Ω	.665v/30.7Ω	80.97
3M Hz	31mV/102.8Ω	.425v/30.7Ω	45.91

NOTE: all voltages are measured peak to peak

VE = -.0011v
VC = -1.5v
VB = -.7088v
VCB = -0.791v

$\beta_0 = 148.8$

$\beta = \frac{\beta_0}{\sqrt{2}} = 105.2$

$f_\beta = f\Big|_{\beta=105.2} = 1.0 \text{ MHz}$

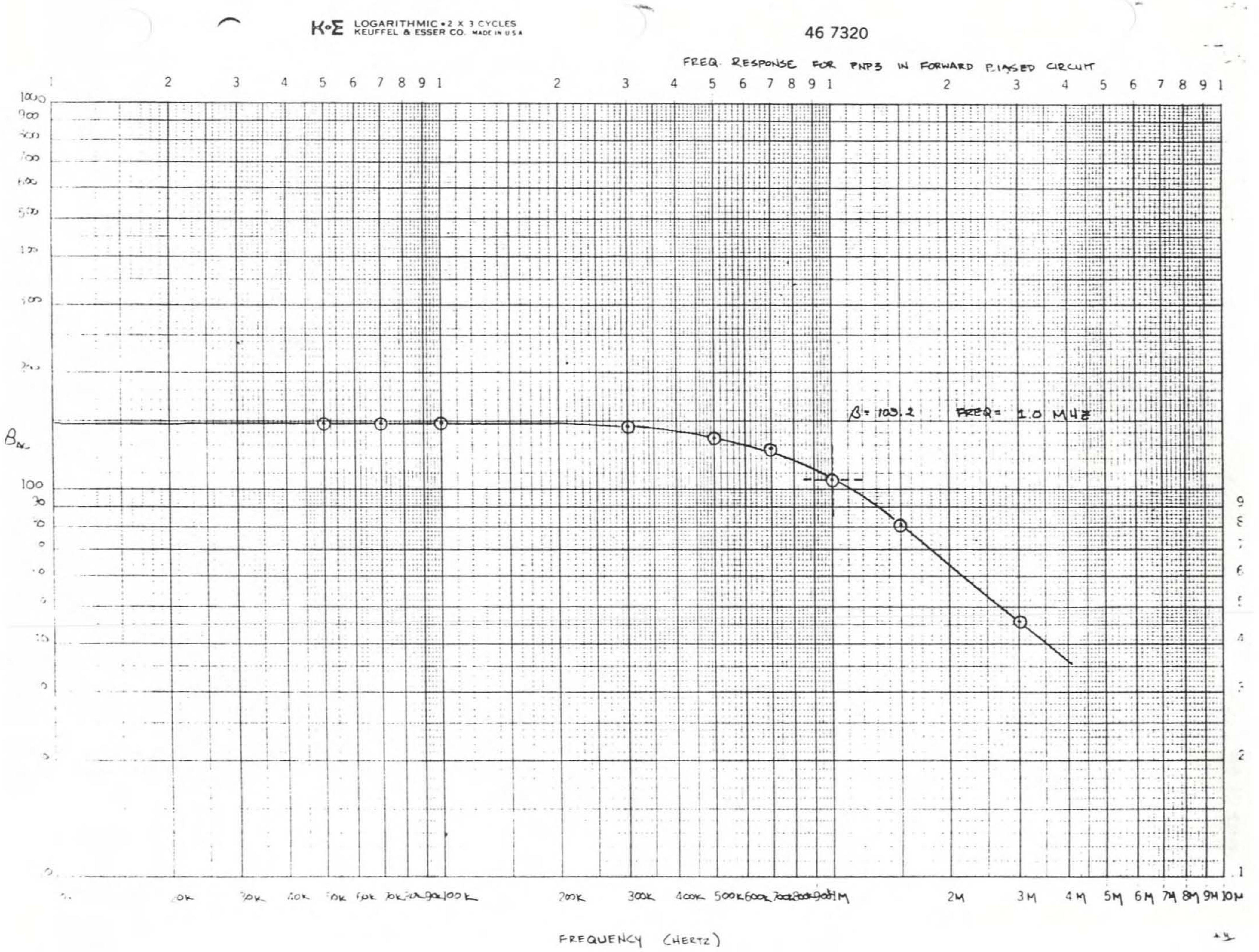
$f_{meas} = (148.8)(1.0\text{MHz}) = 148.8 \text{ MHz}$

$CC\Big|_{VBC=-.791v} = 13.55\text{pF}$ from graph of (VJC+VBC) vs CC

$f_T = \left[1/148.8\text{MHz} - 2\pi(13.55\text{pF})(30.7\Omega) \right]^{-1} = 243.5 \text{ MHz}$

$TF = 1/2\pi(243.5\text{MHz}) - (13.55\text{pF})(10\Omega) = 5.18 \times 10^{-10} \text{ s}$

KH


K&E LOGARITHMIC • 2 X 3 CYCLES KEUFFEL & ESSER CO. MADE IN U.S.A.
46 7320
FREQ. RESPONSE FOR PNP3 IN FORWARD BIASED CIRCUIT
β = 103.2 FREQ = 1.0 MHZ
B_{ac}
100
200K
300K
2M
3M
4M
5M
6M
7M
8M
9M
10M
FREQUENCY (HERTZ)

EXAMPLE: TR

FREQ	I_b	I_e	β_{ac}
50K Hz	10mV/11.6 Ω	.96v/103.4 Ω	10.77
70K Hz	10mV/11.6 Ω	.96v/103.4 Ω	10.77
100K Hz	10mV/11.6 Ω	.94v/103.4 Ω	10.55
150K Hz	10mV/11.6 Ω	.925v/103.4 Ω	10.38
300K Hz	10mV/11.6 Ω	.84v/103.4 Ω	9.42
500K Hz	12.5mV/11.6 Ω	.72v/103.4 Ω	6.46
700K Hz	14mV/11.6 Ω	.62v/103.4 Ω	4.97
1M Hz	15mV/11.6 Ω	.50v/103.4 Ω	3.74
1.5M Hz	20mV/11.6 Ω	.40v/103.4 Ω	2.24
3M Hz	22.5mV/11.6 Ω	.24v/103.4 Ω	1.20

VE = 2.061 v
VC = 0.00 v
VB = -.690 v
VEB = -1.363 v

NOTE: all voltages are measured peak to peak

$\beta_0 = 10.77$

$C_E \big|_{VEB = 1.363v} = 15.6\ pF$ from graph of (VJE + VBE) vs. CE

$\beta = 7.62$

$f_\beta = 410K\ Hz$

$f_{meas} = (410K\ Hz)(10.77) = 4.42\ MHz$

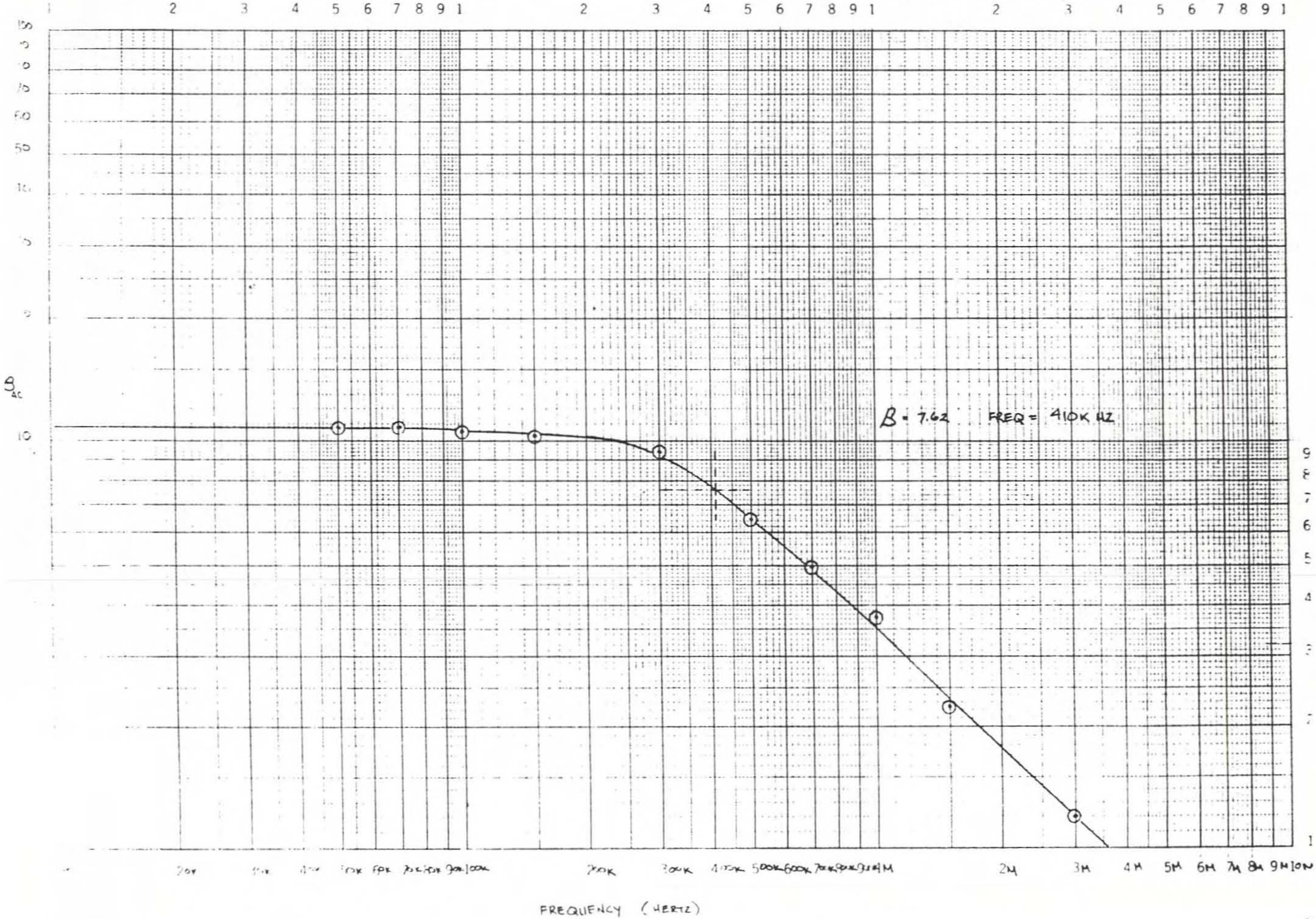
$f_T = \left[1/4.42MHz - 2\pi\ (15.6\ pF)(103.4\ \Omega) \right] = 4.63\ MHz$

$TR = 1/2\pi\ (4.63MHz) - (15.6\ pF)(0.74\ \Omega)$

$= 34.4 \times 10^{-9}$ sec

SH

FREQ RESPONSE OF PNP3 N REVERSE BIASED CIRCUIT



2N2904S, AS, 2N2905S, AS 2N2906, A 2N2907, A (SILICON) 2N3485, A, 2N3486, A

PNP SILICON ANNULAR HERMETIC TRANSISTORS

. . . designed for high-speed switching circuits, DC to VHF amplifier applications and complementary circuitry.

- High DC Current Gain Specified – 0.1 to 500 mAdc
- High Current-Gain–Bandwidth Product – f_T = 200 MHz (Min) @ I_C = 50 mAdc
- Low Collector-Emitter Saturation Voltage – $V_{CE(sat)}$ = 0.4 Vdc (Max) @ I_C = 150 mAdc
- 2N2904,A thru 2N2907,A Complement to NPN 2N2218,A, 2N2219,A, 2N2221,A, 2N2222,A
- JAN, JTX, JTXV Available, Except 2N2904S, AS, 2N3485 and 2N3486

PNP SILICON SWITCHING AND AMPLIFIER TRANSISTORS

CASE 79-02
TO-39
2N2904S,AS
2N2905S,AS

CASE 22-03
(TO-18)
2N2906,A
2N2907,A

CASE 26-03
(TO-46)
2N3485,A
2N3486,A

SELECTOR GUIDE

Device Type	BV_{CEO} I_C = 10 mAdc Volts	h_{FE} I_C = 1.0 mAdc Min	h_{FE} I_C = 150 mAdc Min	h_{FE} I_C = 500 mAdc Min	Package
2N2904 2N2905	40	25 50	40 100	20 30	TO-39
2N2906 2N2907	↓	25 50	40 100	20 30	TO-18
2N3485 2N3486	↓	25 50	40 100	20 30	TO-46
2N2904A 2N2905A	60	40 100	40 100	40 50	TO-39
2N2906A 2N2907A	↓	40 100	40 100	40 50	TO-18
2N3485A 2N3486A	↓	40 100	40 100	40 50	TO-46

*MAXIMUM RATINGS

Rating	Symbol	Non-A Suffix		A-Suffix	Unit
Collector-Emitter Voltage	V_{CEO}	40		60	Vdc
Collector-Base Voltage	V_{CB}	60			Vdc
Emitter-Base Voltage	V_{EB}	5.0			Vdc
Collector Current – Continuous	I_C	600			mAdc
		2N2904,A 2N2905,A	2N2906,A 2N2907,A	2N3485,A 2N3486,A	
Total Device Dissipation @ T_A = 25°C	P_D	600	400	400	mW
Derate above 25°C		3.43	2.28	2.28	mW/°C
Total Device Dissipation @ T_C = 25°C	P_D	3.0	1.8	2.0	Watts
Derate above 25°C		17.2	10.3	11.43	mW/°C
Operating and Storage Junction Temperature Range	T_J, T_{stg}	-65 to +200			°C

*Indicates JEDEC Registered Data

PNP SILICON
WITCHING AND AMPLIFIER
TRANSISTORS

79-02
-39
04S,AS
05S,AS

CASE 22-03
(TO-18)
2N2906,A
2N2907,A

03
.A
.A

*ELECTRICAL CHARACTERISTICS (T_A = 25° unless otherwise noted)

Characteristic		Symbol	Min	Typ	Max	Unit
OFF CHARACTERISTICS						
Collector-Emitter Breakdown Voltage(1) (I_C = 10 mAdc, I_B = 0)	Non-A Suffix A-Suffix	BV_{CEO}	40 60	– –	 –	Vdc
Collector-Base Breakdown Voltage (I_C = 10 μAdc, I_E = 0)		BV_{CBO}	60	–	–	Vdc
Emitter-Base Breakdown Voltage (I_E = 10 μAdc, I_C = 0)		BV_{EBO}	5.0	–	–	Vdc
Collector Cutoff Current (V_{CE} = 30 Vdc, V_{BE} = 0.5 Vdc)		I_{CEX}	–	–	50	nAdc
Collector Cutoff Current (V_{CB} = 50 Vdc, I_E = 0) (V_{CB} = 50 Vdc, I_E = 0, T_A = 150°C)	Non-A Suffix A-Suffix Non-A Suffix A-Suffix	I_{CBO}	– – – –	– – – –	0.020 0.010 20 10	μAdc
Base Cutoff Current (V_{CE} = 30 Vdc, V_{BE} = 0.5 Vdc)		I_B	–	–	50	nAdc
ON CHARACTERISTICS						
DC Current Gain (I_C = 0.1 mAdc, V_{CE} = 10 Vdc)	2N2904,2N2906,2N3485 2N2905,2N2907,2N3486 2N2904A,2N2906A,2N3485A 2N2905A,2N2907A,2N3486A	h_{FE}	20 35 40 75	– – – –	– – – –	–
(I_C = 1.0 mAdc, V_{CE} = 10 Vdc)	2N2904,2N2906,2N3485 2N2905,2N2907,2N3486 2N2904A,2N2906A,2N3485A 2N2905A,2N2907A,2N3486A		25 50 40 100	– – – –	– – – –	
(I_C = 10 mAdc, V_{CE} = 10 Vdc)	2N2904,2N2906,2N3485 2N2905,2N2907,2N3486 2N2904A,2N2906A,2N3485A 2N2905A,2N2907A,2N3486A		35 75 40 100	– – – –	– – – –	
(I_C = 150 mAdc, V_{CE} = 10 Vdc)(1)	2N2904,A,2N2906,A,2N3485,A 2N2905,A,2N2907,A,2N3486,A		40 100	– –	120 300	
(I_C = 500 mAdc, V_{CE} = 10 Vdc)(1)	2N2904,2N2906,2N3485 2N2905,2N2907,2N3486 2N2904A,2N2906A,2N3485A 2N2905A,2N2907A,2N3486A		20 30 40 50	– – – –	– – – –	
Collector-Emitter Saturation Voltage(1) (I_C = 150 mAdc, I_B = 15 mAdc) (I_C = 500 mAdc, I_B = 50 mAdc)		$V_{CE(sat)}$	– –	– –	0.4 1.6	Vdc
Base-Emitter Saturation Voltage (I_C = 150 mAdc, I_B = 15 mAdc)(1) (I_C = 500 mAdc, I_B = 50 mAdc)		$V_{BE(sat)}$	– –	– –	1.3 2.6	Vdc
DYNAMIC CHARACTERISTICS						
Current-Gain–Bandwidth Product(2) (I_C = 50 mAdc, V_{CE} = 20 Vdc, f = 100 MHz)		f_T	200	–	–	MHz
Output Capacitance (V_{CB} = 10 Vdc, I_E = 0, f = 100 kHz)		C_{ob}	–	–	8.0	pF
Input Capacitance (V_{BE} = 2.0 Vdc, I_C = 0, f = 100 kHz)		C_{ib}	–	–	30	pF
SWITCHING CHARACTERISTICS						
Turn-On Time	(V_{CC} = 30 Vdc, I_C = 150 mAdc, I_{B1} = 15 mAdc) (Figure 15a)	t_{on}	–	26	45	ns
Delay Time		t_d	–	6.0	10	ns
Rise Time		t_r	–	20	40	ns
Turn-Off Time	(V_{CC} = 6.0 Vdc, I_C = 150 mAdc, I_{B1} = I_{B2} = 15 mAdc) (Figure 15b)	t_{off}	–	70	180	ns
Storage Time		t_s	–	50	80	ns
Fall Time		t_f	–	20	150	ns

*Indicates JEDEC Registered Data.
(1) Pulse Test: Pulse Width ≤ 300 μs, Duty Cycle ≤ 2.0%
(2) f_T is defined as the frequency at which $|h_{fe}|$ extrapolates to unity.

FIGURE 15a – DELAY AND RISE TIME TEST CIRCUIT

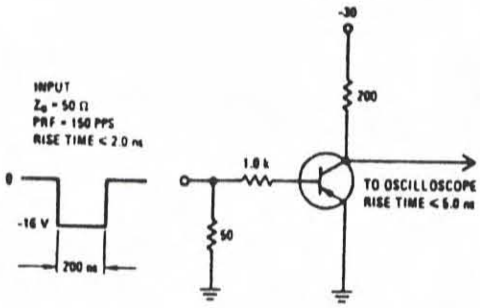
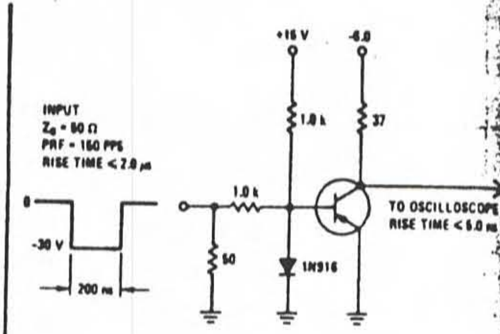
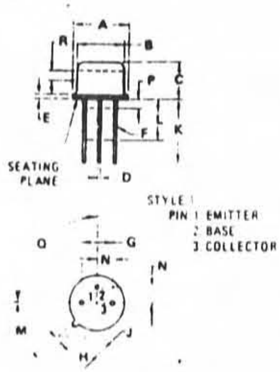


FIGURE 15b – STORAGE AND FALL TIME TEST CIRCUIT



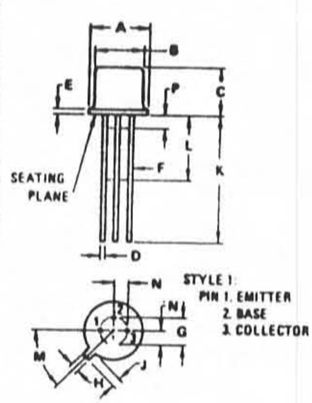
OUTLINE DIMENSIONS



DIM	MILLIMETERS MIN	MILLIMETERS MAX	INCHES MIN	INCHES MAX
A	8.89	9.40	0.350	0.370
B	8.00	8.51	0.315	0.335
C	6.10	6.60	0.240	0.260
D	0.406	0.533	0.016	0.021
E	0.229	3.18	0.009	0.125
F	0.406	0.483	0.016	0.019
G	4.83	5.33	0.190	0.210
H	0.711	0.864	0.028	0.034
J	0.737	1.02	0.029	0.040
K	12.70	–	0.500	
L	6.35	–	0.250	
M	45° NOM		45° NOM	
P		1.27		0.050
Q	90° NOM		90° NOM	
R	2.54		0.100	

All JEDEC dimensions and notes apply.

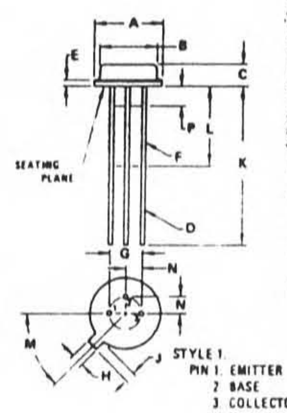
CASE 79-02
TO-39



DIM	MILLIMETERS MIN	MILLIMETERS MAX	INCHES MIN	INCHES MAX
A	5.31	5.84	0.209	0.230
B	4.52	4.95	0.178	0.195
C	4.32	5.33	0.170	0.210
D	0.406	0.533	0.016	0.021
E	–	0.762	–	0.030
F	0.406	0.483	0.016	0.019
G	2.54 BSC		0.100 BSC	
H	0.914	1.17	0.036	0.046
J	0.711	1.22	0.028	0.048
K	12.70	–	0.500	–
L	6.35	–	0.250	–
M	45° BSC		45° BSC	
N	1.27 BSC		0.050 BSC	
P	–	1.27	–	0.050

All JEDEC notes and dimensions apply.

CASE 22
TO-18



DIM	MILLIMETERS MIN	MILLIMETERS MAX	INCHES MIN	INCHES MAX
A	5.31	5.84	0.209	0.230
B	4.52	4.95	0.178	0.195
C	1.65	2.16	0.065	0.085
D	0.406	0.533	0.016	0.021
E	–	1.02	–	0.040
F	0.305	0.483	0.012	0.019
G	2.54 BSC		0.100 BSC	
H	0.914	1.17	0.036	0.046
J	0.711	1.22	0.028	0.048
K	12.70	–	0.500	–
L	6.35		0.250	–
M	45° BSC		45° BSC	
N	1.27 BSC		0.050 BSC	
P	–	1.27	–	0.050

All JEDEC dimensions and notes apply.

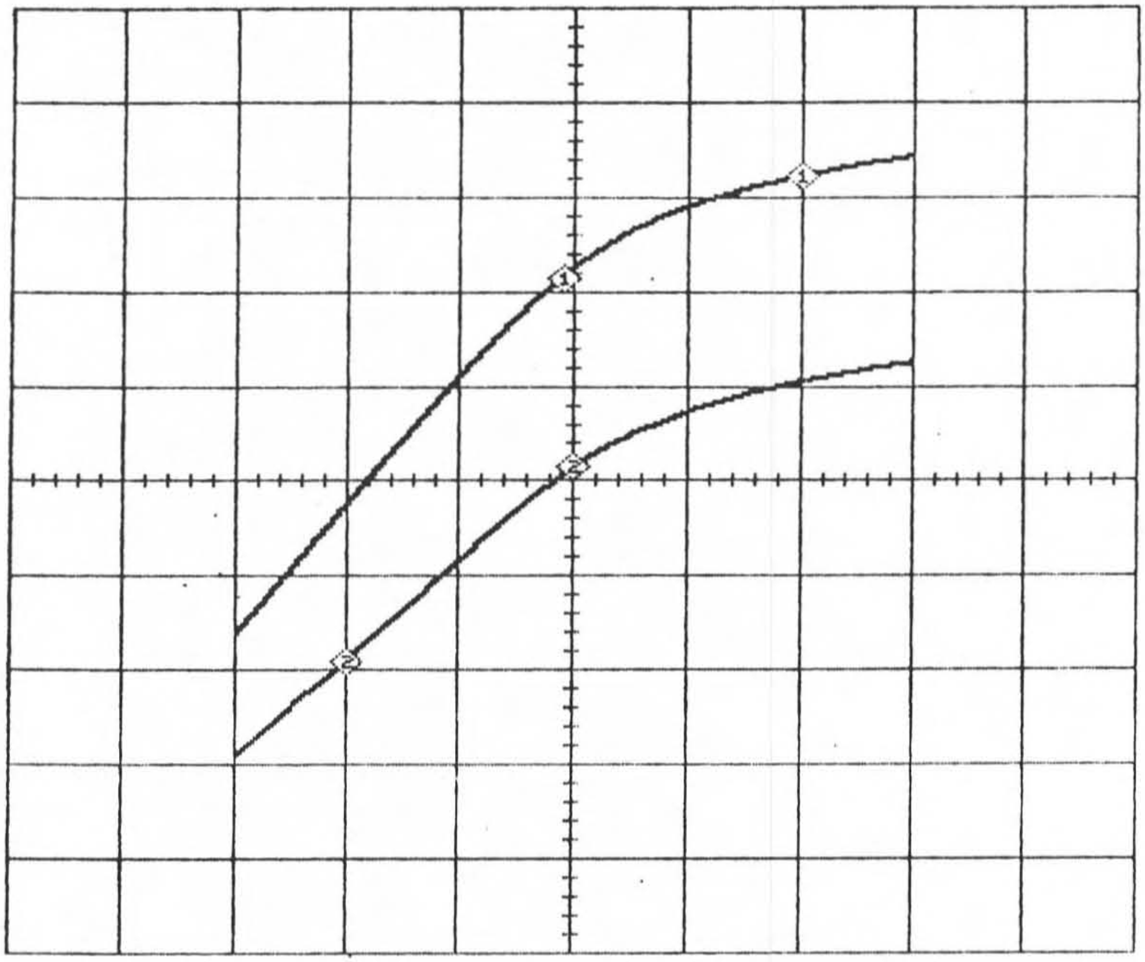
CASE 26
TO-46

EXAMPLE:

SPICE RUN OF 2N2907 TRANSISTOR MODEL

FORWARD DC CHARACTERISTICS

SPICE ANALYSIS OF OUT.OUT on 1-03-86 page 1



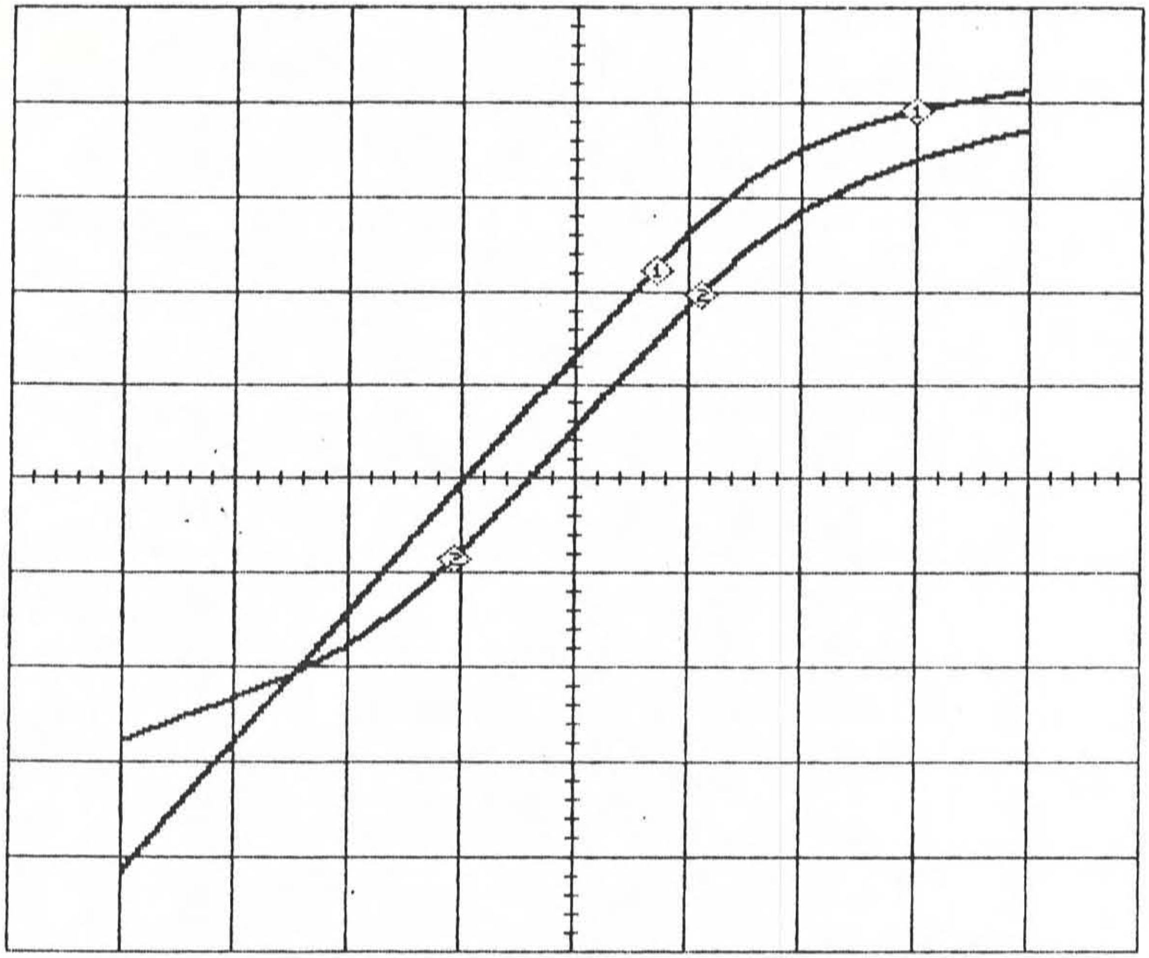
CH 1 IDB(VIC) vs VBE	CURSOR	LEFT	RIGHT	DIFFERENCE
YSCALE 20DBA/DIV				
YZERO -96.0 DBA	VER	-52.8 DBA	-31.4 DBA	21.4 DBA
XSCALE 100MV/DIV				
XZERO 700MV	HOR	690MV	900MV	210MV

CH 2 IDB(VIB) vs VBE	CURSOR	LEFT	RIGHT	DIFFERENCE
YSCALE 20DBA/DIV				
YZERO -96.0 DBA	VER	-134 DBA	-93.1 DBA	40.9 DBA
XSCALE 100MV/DIV				
XZERO 700MV	HOR	500MV	700MV	200MV

```
.MODEL PARAM PNP (IS=1.10E-12 BF=202 BR=6 NF=1.21 RB=700.0
+       RC=10.0 RE=0.74 IKF=750E-3 IKR=3.0E-3 VAF=48.2 VAR=7.3
+       NC=4.483 ISC=3.55E-9 NR=1.22 NE=1.92 ISE=6.67E-12
+       TF=5.2E-10 CJE=23.0E-12 VJE=0.85 MJE=1.254 CJC=19.4E-12
        VJC=0.5 MJC=0.20 TR=34.3E-9)
```

REVERSE DC CHARACTERISTICS

SPICE ANALYSIS OF OUT.OUT on 1-03-86 page 1



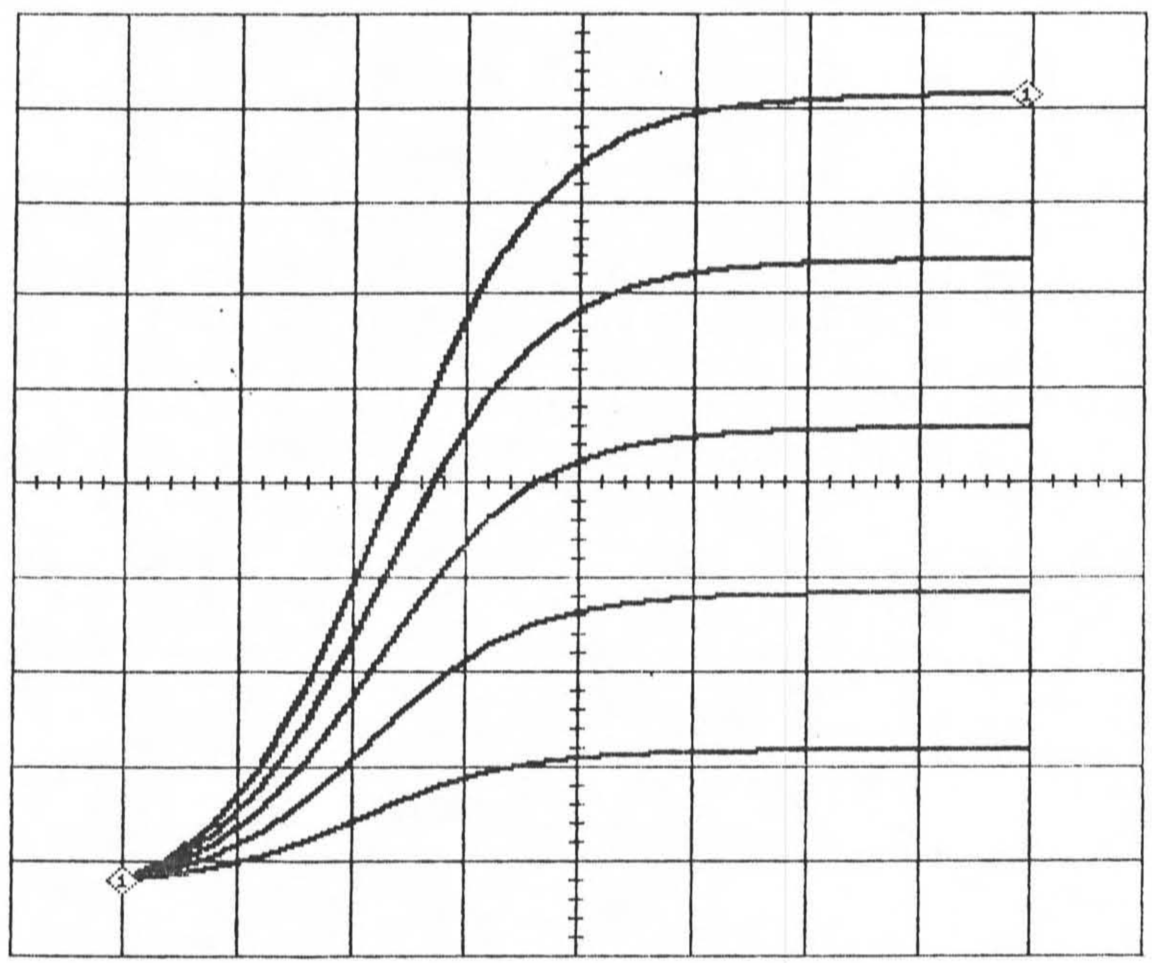
CH 1 IDB(VIE) vs VBC	CURSOR	LEFT	RIGHT	DIFFERENCE
YSCALE 20DBA/DIV				
YZERO -100.0 DBA	VER	-55.3 DBA	-21.8 DBA	33.5 DBA
XSCALE 100MV/DIV				
XZERO 600MV	HOR	670MV	900MV	230MV

CH 2 IDB(VIB) vs VBC	CURSOR	LEFT	RIGHT	DIFFERENCE
YSCALE 20DBA/DIV				
YZERO -100.0 DBA	VER	-117 DBA	-60.8 DBA	56.1 DBA
XSCALE 100MV/DIV				
XZERO 600MV	HOR	495MV	710MV	215MV

```
.MODEL PARAM PNP (IS=1.10E-12 BF=202 BR=6 NF=1.21 RB=1.5
+       RC=.5 RE=0.74 IKF=750E-3 IKR=100E-3 VAF=48.2 VAR=7.3
        NC=4.483 ISC=3.55E-9 NR=1.22 NE=1.92 ISE=6.67E-12
        TF=5.2E-10 CJE=23.0E-12 VJE=0.85 MJE=1.254 CJC=19.4E-12
+       VJC=0.5 MJC=0.20 TR=34.3E-9)
```

COLLECTOR TRACER CURVES

SPICE ANALYSIS OF TRACE.OUT on 1-03-86 page 1

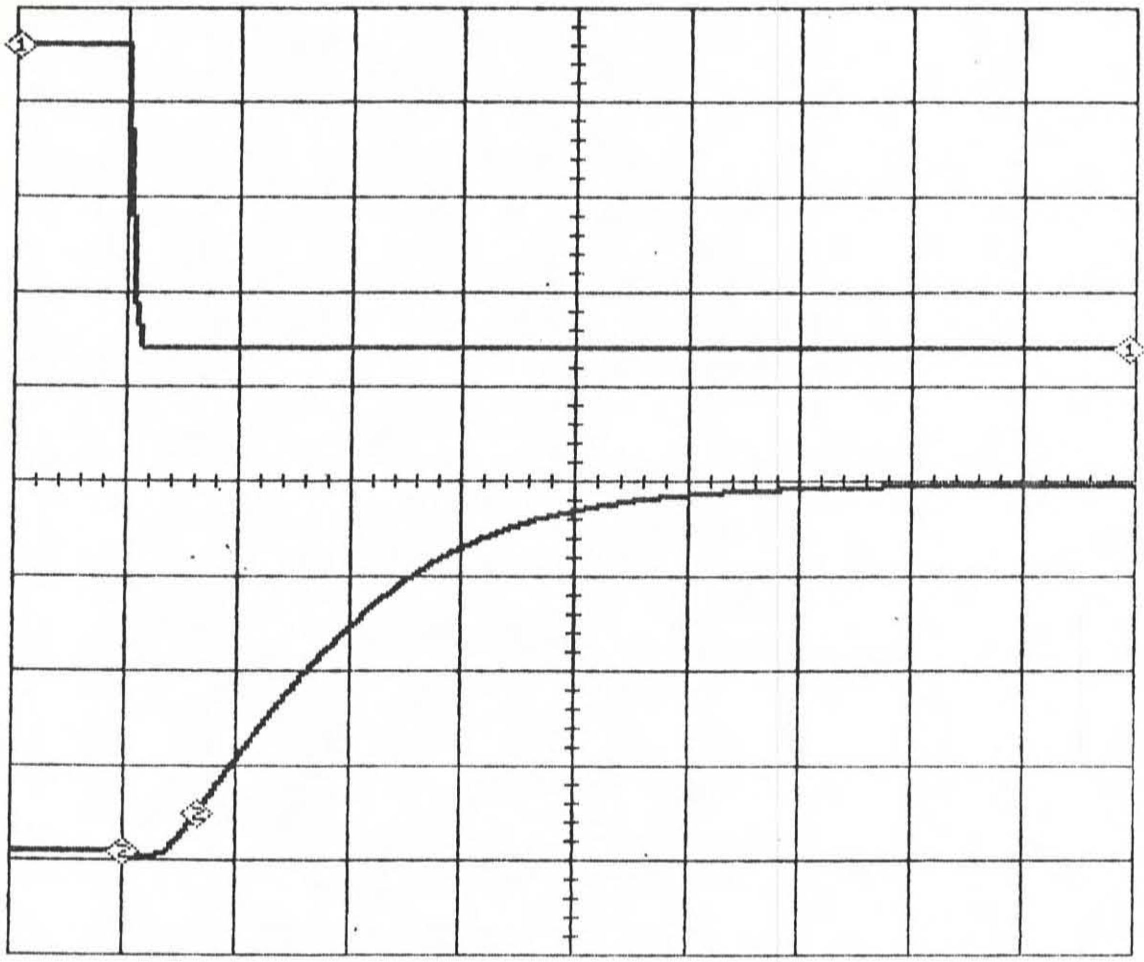


CH 1 I(VIC) vs VCE	CURSOR	LEFT	RIGHT	DIFFERENCE
YSCALE 1MA/DIV				
YZERO 4.20MA	VER	-2.08UA	8.34MA	8.35MA
XSCALE 50MV/DIV				
XZERO 200MV	HOR	9.31NV	397MV	397MV

```
.MODEL PARAM PNP (IS=1.10E-12 BF=250 BR=6 NF=1.21 RB=40
       RC=1 RE=0.74 IKF=750E-3 IKR=3E-3 VAF=48.2 VAR=7.3
       NC=4.483 ISC=3.55E-9 NR=1.22 NE=1.92 ISE=6.67E-12
+      TF=5.2E-10 CJE=23.0E-12 VJE=0.85 MJE=1.254 CJC=19.4E-12
+      VJC=0.5 MJC=0.20 TR=34.3E-9)
```

RISE TIME TEST

SPICE ANALYSIS OF RT-2907.OUT on 1-03-86 page 1



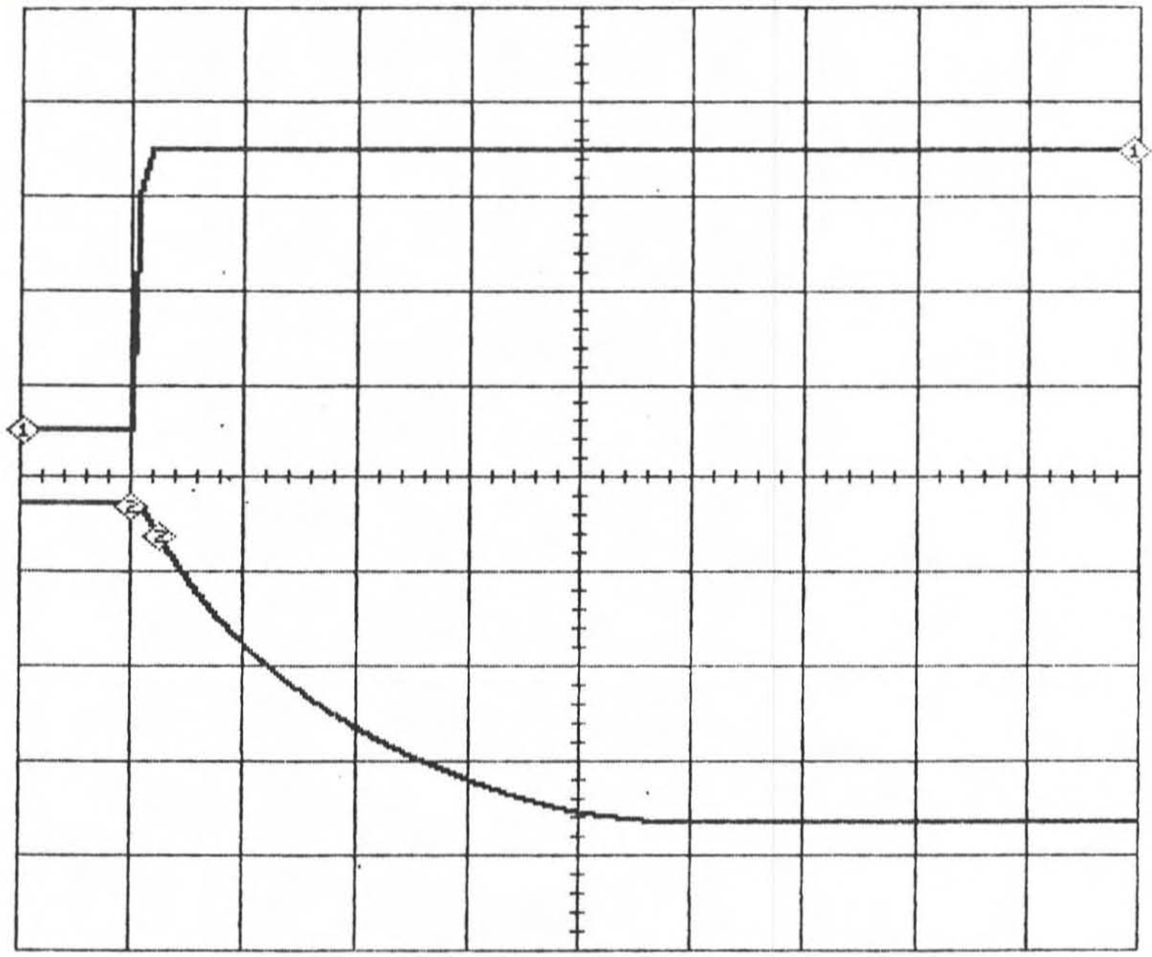
CH 1 V(1) vs TIME	CURSOR	LEFT	RIGHT	DIFFERENCE
YSCALE 5V/DIV				
YZERO -23.0 V	VER	0.00 V	-16.0 V	-16.0 V
XSCALE 10NSEC/DIV				
XZERO 50.0NSEC	HOR	2.00FSEC	99.5NSEC	99.5NSEC

CH 2 V(3) vs TIME	CURSOR	LEFT	RIGHT	DIFFERENCE
YSCALE 5V/DIV				
YZERO -10.4 V	VER	-30.0 V	-28.0 V	2.05 V
XSCALE 10NSEC/DIV				
XZERO 50.0NSEC	HOR	10.0NSEC	16.5NSEC	6.50NSEC

```
MODEL PARAM PNP (IS=1.10E-12 BF=202 BR=6 NF=1.21 RB=350
       RC=10 RE=0.74 IKF=4.0E-3 IKR=3.0E-3 VAF=48.2 VAR=7.3
+      NC=4.483 ISC=3.55E-9 NR=1.22 NE=1.92 ISE=6.67E-12
+      TF=5.2E-10 CJE=23.0E-12 VJE=0.85 MJE=1.254 CJC=19.4E-12
+      VJC=0.5 MJC=0.20 TR=34.3E-9)
```

FALL TIME TEST

SPICE ANALYSIS OF FT-2907.OUT on 1-03-86 page 1



CH 1 V(1) vs TIME	CURSOR	LEFT	RIGHT	DIFFERENCE
YSCALE 10V/DIV				
YZERO -35.0 V	VER	-30.0 V	0.00 V	30.0 V
XSCALE 10NSEC/DIV				
XZERO 50.0NSEC	HOR	2.00FSEC	99.5NSEC	99.5NSEC

CH 2 V(3) vs TIME	CURSOR	LEFT	RIGHT	DIFFERENCE
YSCALE 500MV/DIV				
YZERO -4.16 V	VER	-4.31 V	-4.48 V	-170MV
XSCALE 10NSEC/DIV				
XZERO 50.0NSEC	HOR	10.0NSEC	12.5NSEC	2.50NSEC

```
.MODEL PARAM PNP (IS=1.10E-12 BF=202 BR=6 NF=1.21 RB=1.5K
+       RC=10 RE=0.74 IKF=4.0E-3 IKR=3.0E-3 VAF=48.2 VAR=7.3
+       NC=4.483 ISC=3.55E-9 NR=1.22 NE=1.92 ISE=6.67E-12
+       TF=5.2E-10 CJE=23.0E-12 VJE=0.85 MJE=1.254 CJC=19.4E-12
+       VJC=0.5 MJC=0.20 TR=34.3E-9)
```

INTRODUCTION:

SPICE contains "built-in" equations for the Gummel-Poon model of a PNP Bipolar Junction Transistor. The model diagram and defining equations are listed in the following section. Of the 40 parameters used to characterize the transistor, 25 of them have have been calculated to customize the Gummel-Poon model to simulate the 2N2907A PNP BJT.

BACKGROUND:

JA = non-ideal forward region base current
JB = ideal forward region base current
JC = non-ideal inverse region base current
JD = ideal inverse region base current
JF = forward region dependent current
JR = inverse region dependent current
CC = collector junction capacitance
CE = emitter junction capacitance
RC = collector bulk resistance
RB = base bulk resistance
RE = emitter bulk resistance
R1 = collector-base junction leakage resistance*
R2 = emitter-base junction leakage resistance*

* not included in SPICE model

************ USER'S GUIDE TO USING THE 'BUILD' COMMAND ************

BUILD.BAT is a batch command file run on an IBM PC's Disk Operating System and used in conjunction with Intusoft's SPICE program. BUILD allows an operator the freedom to run a specific model card in any particular circuit layout without having to edit the circuit. After the circuit is completed, BUILD automatically runs SPICE on the circuit.

The format to execute BUILD.BAT is

```
BUILD <circuit> <model name> <output file name>
```

where,

<circuit> = circuit files ending with the filename extension of .TST
<model name> = model card files ending with the filename extension of .MOD
<output file name> = the name of the completed circuit

NOTES:
1. The filename extensions are omitted in the command.
2. If the batch command needs to be terminated at any time, type <CTL> <BREAK>.
3. Do not use any output file name identical with either the circuit file name or the model card name. If this happens, BUILD may delete a current file in the process.
4. The circuit files which are named with simply the type of device (i.e. -PNP,-NPN) are generic in nature. They can be used to test the model card of any specific device. These tests will help in the tweaking and altering of device parameters in the model card.

The current list of circuit files include:

- FWD-PNP.TST - forward DC characteristics test of a PNP transistor
- FWD-NPN.TST - forward DC characteristics test of a NPN transistor
- REV-PNP.TST - reverse DC characteristics test of a PNP transistor
- REV-NPN.TST - reverse DC characteristics test of a NPN transistor
- TRC-PNP.TST - collector trace curves of a PNP transistor
- TRC-NPN.TST - collector trace curves of a NPN transistor
- RT-2907.TST - rise time test of a 2N2907A PNP transistor
- RT-2222.TST - rise time test of a 2N2222A NPN transistor
- FT-2907.TST - fall time test of a 2N2907A PNP transistor
- FT-2222.TST - fall time test of a 2N2222A NPN transistor

The current list of model cards include:

- 2907.MOD - 2N2907A bipolar PNP transistor
- 2222.MOD - 2N2222A bipolar NPN transistor

Example:

If an operator wants to run the collector trace curves of the 2N2907A transistor, the command would be

```
BUILD TRC-PNP 2907 CURVES
```

where the built card would be called CURVES.CIR and the SPICE output would be called CURVES.OUT. Remember that the filename extensions are omitted in the command.

>DIR

```
 Volume in drive C has no label
 Directory of  C:\SPICE\CIRCUITS\KH\CALLAHAN

.            <DIR>       11-11-85  11:55a
..           <DIR>       11-11-85  11:55a
TT                   0   12-15-85   8:17a
BUILD    BAT        48   12-14-85  10:42a
END      DAT         9   12-13-85   4:40p
SPICE    DOC     52642   10-15-85   8:44a
FWD-PNP  TST       166   12-13-85   4:47p
FWD-NPN  TST       167   12-13-85   4:49p
REV-PNP  TST       166   12-15-85   8:09a
REV-NPN  TST       166   12-14-85   2:33p
TRC-PNP  TST       190   12-14-85  10:26a
TRC-NPN  TST       190   12-14-85  10:27a
RT-2907  TST       243   12-14-85  11:08a
RT-2222  TST       247   12-14-85  11:12a
FT-2907  TST       403   12-14-85  11:16a
FT-2222  TST       376   12-14-85  11:21a
2907     MOD       283   12-14-85  11:19a
2222     MOD       205   12-14-85  11:13a
USER_MAN TXT      2654   12-15-85   8:48a
       19 File(s)   1527808 bytes free
```

>BUILD.BAT

```
COPY %1.TST + %2.MOD + END.DAT %3.CIR
IS %3.CIR
```

>END.DAT

```
*
.END
```

>2907.MOD

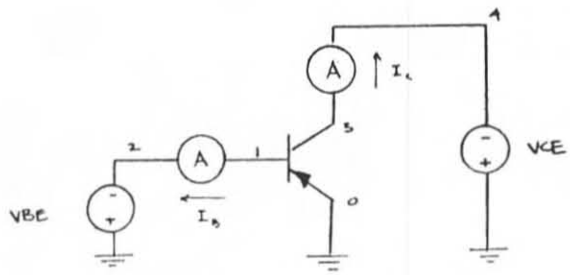
```
.MODEL PARAM PNP (IS=1.10E-12 BF=202 BR=6 NF=1.21 RB=350.0
+       RC=10.0 RE=0.74 IKF=4.0E-3 IKR=3.0E-3 VAF=48.2 VAR=7.3
+       NC=4.483 ISC=3.55E-9 NR=1.22 NE=1.92 ISE=6.67E-12
+       TF=5.2E-10 CJE=23.0E-12 VJE=0.85 MJE=1.254 CJC=19.4E-12
+       VJC=0.5 MJC=0.20 TR=34.3E-9)
```

>2222.MOD

```
.MODEL PARAM NPN(IS=1.9E-14 BF=150 VAF=100 IKF=.175 ISE=5E-11 NE=2.5
+       BR=7.5 VAR=6.38 IKR=.035 ISC=8.7E-12 NC=1.5 RB=40 RE=.41 RC=.4
+       CJE=26PF TF=.15E-9 CJC=11PF TR=2E-9 NR=.8 KF=3.2E-17)
```

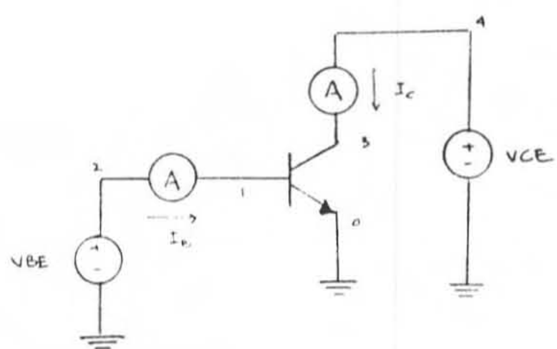
>FWD-PNP.TST

```
FORWARD DC CHARACTERISTICS OF A PNP TRANSISTOR
*
QPNP 3 1 0 PARAM
VIB  1 2
VBE  0 2
VIC  3 4
VCE  0 4 DC 1.0V
*
.DC VBE .4V 1V .05V
.PRINT DC I(VIB) I(VIC)
*
```



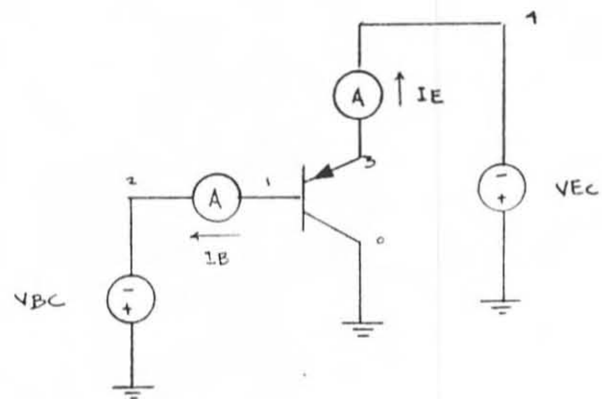
>FWD-NPN.TST

```
FORWARD DC CHARACTERISTICS OF A NPN TRANSISTOR
*
QNPN 3 1 0 PARAM
VIB  2 1
VBE  2 0
VIC  4 3
VCE  4 0 DC 1.0V
*
.DC VBE .4V 1V .05V
.PRINT DC I(VIB) I(VIC)
*
```



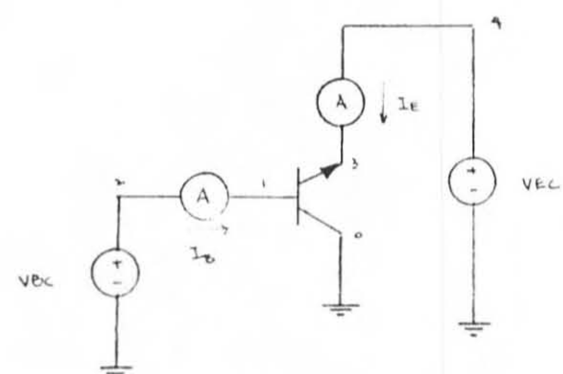
\>REV-PNP.TST

```
REVERSE DC CHARACTERISTICS OF A PNP TRANSISTOR
*
QPNP 0 1 3 PARAM
VIB  1 2
VBC  0 2
VIE  3 4
VEC  0 4 DC 1.0V
*
.DC VBC .2V 1V .05V
.PRINT DC I(VIB) I(VIE)
*
```



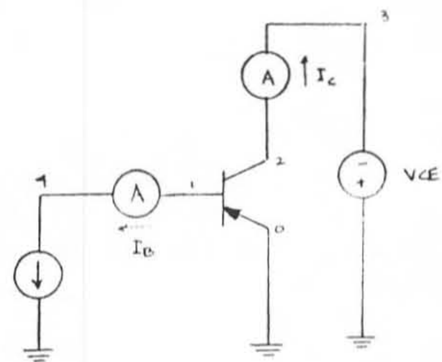
\>REV-NPN.TST

```
REVERSE DC CHARACTERISTICS OF A NPN TRANSISTOR
*
QNPN 0 1 3 PARAM
VIB  2 1
VBC  2 0
VIE  4 3
VEC  4 0 DC 1.0V
*
.DC VBC .2V 1V .05V
.PRINT DC I(VIB) I(VIE)
*
```



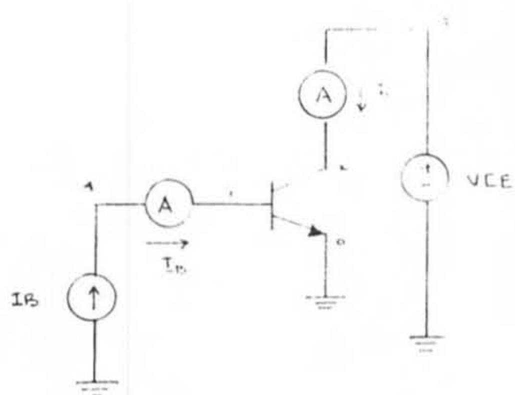
>TRC-PNP.TST

```
COLLECTOR TRACE CURVES OF A PNP TRANSISTOR
*
QPNP 2 1 0 PARAM
IB   4 0
VIC  2 3
VCE  0 3
VIB  1 4
*
.DC VCE 0V .4V .02V IB 10UA 50UA 10UA
.PRINT DC I(VIC)
.OPTIONS LIMPTS=1000
*
```



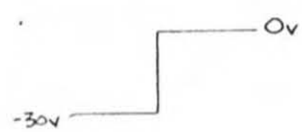
>TRC-NPN.TST

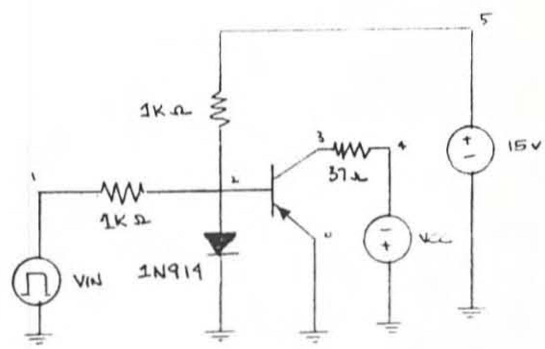
```
COLLECTOR TRACE CURVES OF A NPN TRANSISTOR
*
QNPN 2 1 0 PARAM
IB   0 4
VIC  3 2
VCE  3 0
VIB  4 1
*
.DC VCE 0V .4V .02V IB 10UA 50UA 10UA
.PRINT DC I(VIC)
.OPTIONS LIMPTS=1000
*
```



>FT-2907.TST

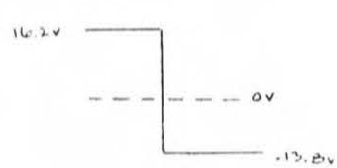
```
FALL TIME TEST OF 2N2907 PNP TRANSISTOR
*
VIN  1 0   PULSE (-30V 0V 10NS 1NS 1NS 200NS 1000NS)
R1   1 2   1KOHMS
QPNP 3 2 0 PARAM
R37  4 3   37OHMS
VCC  4 0   -6V
R2   2 5   1KOHMS
D1   2 0   DIODE
V15  5 0   15V
*
.MODEL DIODE D(RS=.464 CJO=1.37PF IS=1.29E-9 N=1.78 VJ=.6
+       TT=1.15E-8 M=.0181 BV=125V IBV=100UA)
*
.TRAN 1NS 100NS
.PRINT TRAN V(1) V(2) V(3)
.OPTIONS LIMPTS=500
*
```

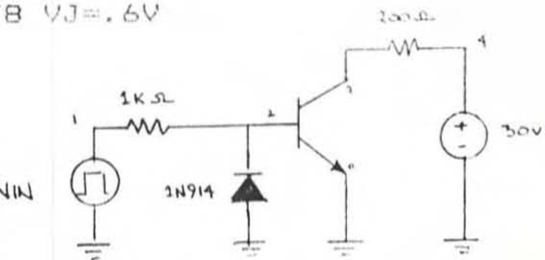




>FT-2222.TST

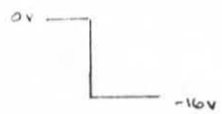
```
FALL TIME TEST FOR 2N2222A NPN TRAMSISTOR
*
VIN  1 0   PULSE (16.2V -13.8V 10NS 1NS 1NS 200NS 212NS)
R1K  1 2   1KOHMS
QNPN 3 2 0 PARAM
R200 4 3   200OHMS
VCC  4 0   30V
D1   0 2   DIODE
*
.MODEL DIODE D(RS=.464 CJO=1.37PF IS=1.29E-9 N=1.78 VJ=.6V
+       TT=1.15E-8 M=.0181 BV=125V IBV=100UA)
*
.TRAN 1NS 200NS
.PRINT TRAN V(1) V(2) V(3)
  TIONS LIMPTS=500
*
```

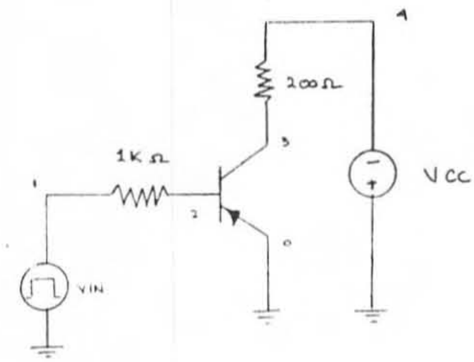




>RT-2907.TST

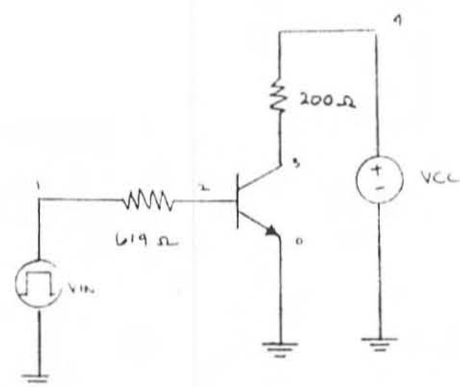
```
RISE TIME TEST FOR 2N2907A TRANSISTOR
*
VIN  1 0   PULSE (0V -16V 10NS 1NS 1NS 200NS 1000NS)
R1K  1 2   1KOHMS
QPNP 3 2 0 PARAM
R200 4 3   200OHMS
VCC  4 0   -30V
*
.TRAN .5NS 100NS
.PRINT TRAN V(1) V(2) V(3)
.OPTIONS LIMPTS=500
*
```

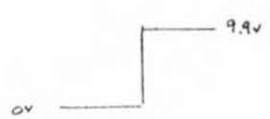




>RT-2222.TST

```
RISE TIME TEST FOR 2N2222A NPN TRANSISTOR
*
VIN  1 0   PULSE (0V 9.9V 10NS 1NS 1NS 200NS 1000NS)
R619 1 2   619OHMS
QNPN 3 2 0 PARAM
R200 4 3   200OHMS
VCC  4 0   30V
*
.TRAN .5NS 100NS
.PRINT TRAN V(1) V(2) V(3)
.OPTIONS LIMPTS=500
*
```





D. A.

REFERENCES:

1. HOOVER, J.W. "HANDBOOK OF SEMICONDUCTOR MODELING FOR SPICE2", MCDONNELL DOUGLAS CORP. AUGUST 1983

3. GETREU, IAN "MODELING THE BIPOLAR TRANSISTOR", TEKTRONIX INC., BEAVERTON OR, 1976

4. YOUNG P.A. ALEXANDER D.R. ANTINONE R.T., SIMON, ROBERT G. "HANDBOOK OF MODLEING FOR CIRCUIT ANALYSIS-INCLUDING RADIATION EFFECTS", BDM CORPORATION, ALBUQUERQUE, NM AFWL-TR-79-86, AIR FORCE WEAPONS LABORATORY, KIRTLAND AIRFORCE BASE, ALBUQUERQUE NM available from DEFENSE TECHNICAL INFORMATION CENTER as AD A071857

5. NAGEL, LAURENCE W., "SPICE2: A COMPUTER PROGRAM TO SIMULATE SEMICONDUCTOR CIRCUITS", MEMORANDUM No. ERL-M520, ELECTRONICS RESEARCH LABORATORY, UNIVERSITY OF CALIFORNIA, BERKELEY, BERKELEY, CA.

6. BOWER, J.C., ENGLISH, N., NIENHAUS. E.A., "PARAMETER DETERMINATION TECHNIQUES FOR THE GUMMEL-POON TRANSISTOR MODEL", UNIVERSITY OF FLORIDA, TAMPA, FL.

and yet another

DEFINITIVE HANDBOOK OF MODELING SEMICONDUCTOR DEVICES

subtitled "Modeling can be fun!"

Contains Procedures for

MODELING DIODES & TRANSISTORS

Contributions By

Charles E. Hymowitz
Kenneth Horita
Jeff T. Robson
Kirk T. Ober

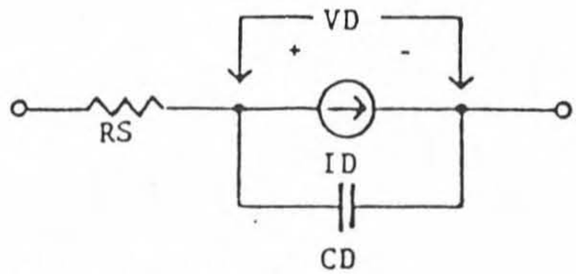
January, 14 1986

CONTENTS

APPENDICES

I. INTRODUCTION

The behavior of a diode model relies heavily on a set of prescribed parameters. These parameters govern the overall electrical habits of the device. Some parameters are readily available from a manufacturers data sheet for a given device. Other parameters are not as evident or must be calculated from bias data. In some cases parameters are not given in the data sheets so circuits must be developed to measure them.
An understanding of diode modeling is fundamental to the task of modeling any semiconductor device.



Spice diode model

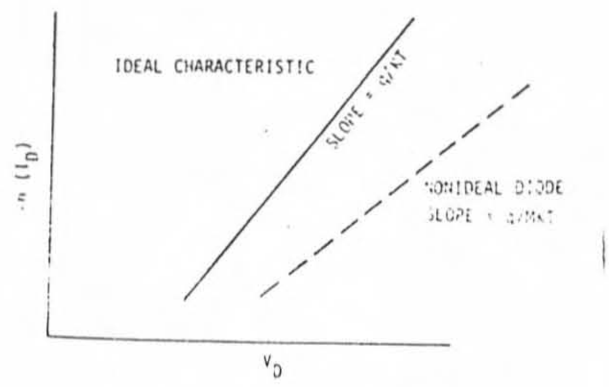
The following pages contain procedures on how to derive the parameters necessary for SPICE to model a semiconductor diode. In particular, the 1N5811 rectifier and 1N4148 switching diodes are modeled here but the procedure may be applied to other diodes. Sample calculations for several parameters appear at the end of the procedures.

A comparison is made between the model and the actual device for the transient time experiment. SPICE was run on an IBM-PC with graphics by INTUSOFT.

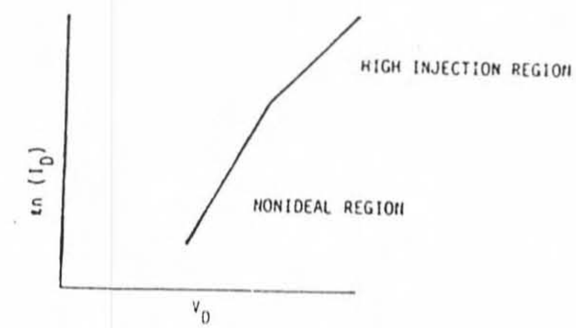
II. DIODE MODELING METHODOLOGY

The foundation of all diode models is the diode equation which relates the forward diode current to the forward diode voltage. Forward bias data on a diode is both easily obtained and yield three important SPICE parameters. These parameters are the emission coefficient (N), the saturation current (Is) and the parasitic (ohmic) resistance (Rs). The basic diode equation (SEE equation #2) gives the gross first order I/V characteristic. In circuits where the details of the diode response are important to proper operation, additional model parameters must be included to simulate second order effects. The variation of the default Spice diode curve as each parameter is added, can be seen on the next page. For example, the emission coefficient, N, shifts the curve up and down, particularly in the non-ideal region. Whereas, the bulk resistance affects the curve in the high ohmic region by bending the curve. In addition to the methods of laboratory data measurement and data sheet parameter extraction, one of the quickest ways to obtain a fairly accurate model for a particular application is to parameter "tweak". This is done by inserting "Ball Park" numbers into the model and "tweaking" the parameters until simulated curves look like some known data curves such as those from a data sheet. This procedure is discussed in greater detail in the Transistor Modeling procedures.

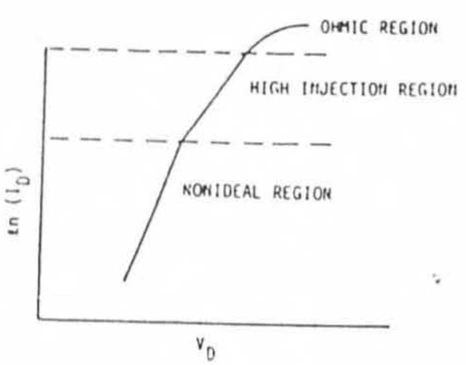
Obtaining the desired data is done through use of a log ID vs VD graphs in the forward region. Most data sheets supply these graphs from which data may be extracted. A more accurate way is to obtain the data experimentally and plot the graph manually or through the use of a computer graphics package such as SOFT_SCOPE (by INTUSOFT).



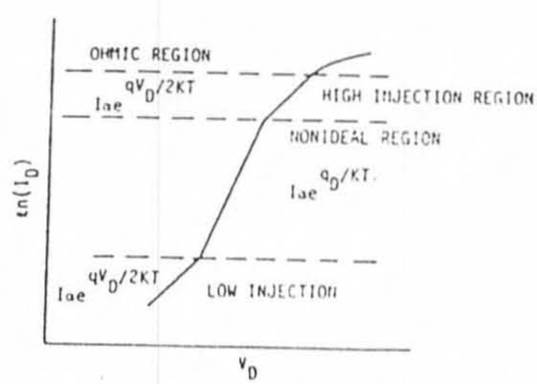
I-V Characteristics Using an Emission Constant



Inclusion of High Injection

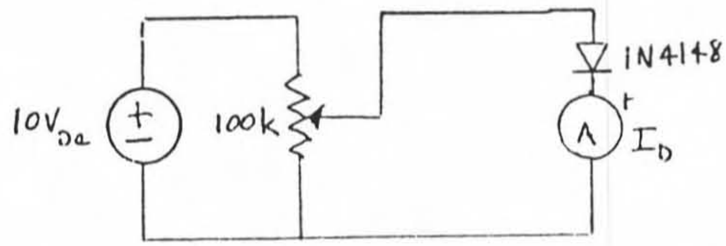


Inclusion of Bulk Resistance



Nonideal Diode Behavior

The following circuit will yield the data necessary for a forward current versus voltage plot for a 1N4148 diode.



The following data, an average of readings for several diodes, was collected.

ID (mA)	VD (volts)
0.1	0.4877
0.2	0.5232
0.5	0.5689
1.0	0.6037
2.0	0.6402
5.0	0.6902
10.0	0.7328
20.0	0.7784
50.0	0.8621
100.0	0.9495
200.0	1.073
500.0	1.277
1000.0	1.780

Similar data was compiled for the 1N5811 diode using the same test circuit with different voltage supply and resistance values:

ID (A)	VD (volts)
.01	0.5341
.02	0.5635
.05	0.6032
0.1	0.6344
0.2	0.6657
0.5	0.7068
1.0	0.7277
2.0	0.7402
5.0	0.8366
8.0	0.8514

Applying this data graphically results in the following plots.

FORWARD BIAS CHARACTERISTIC INITIAL

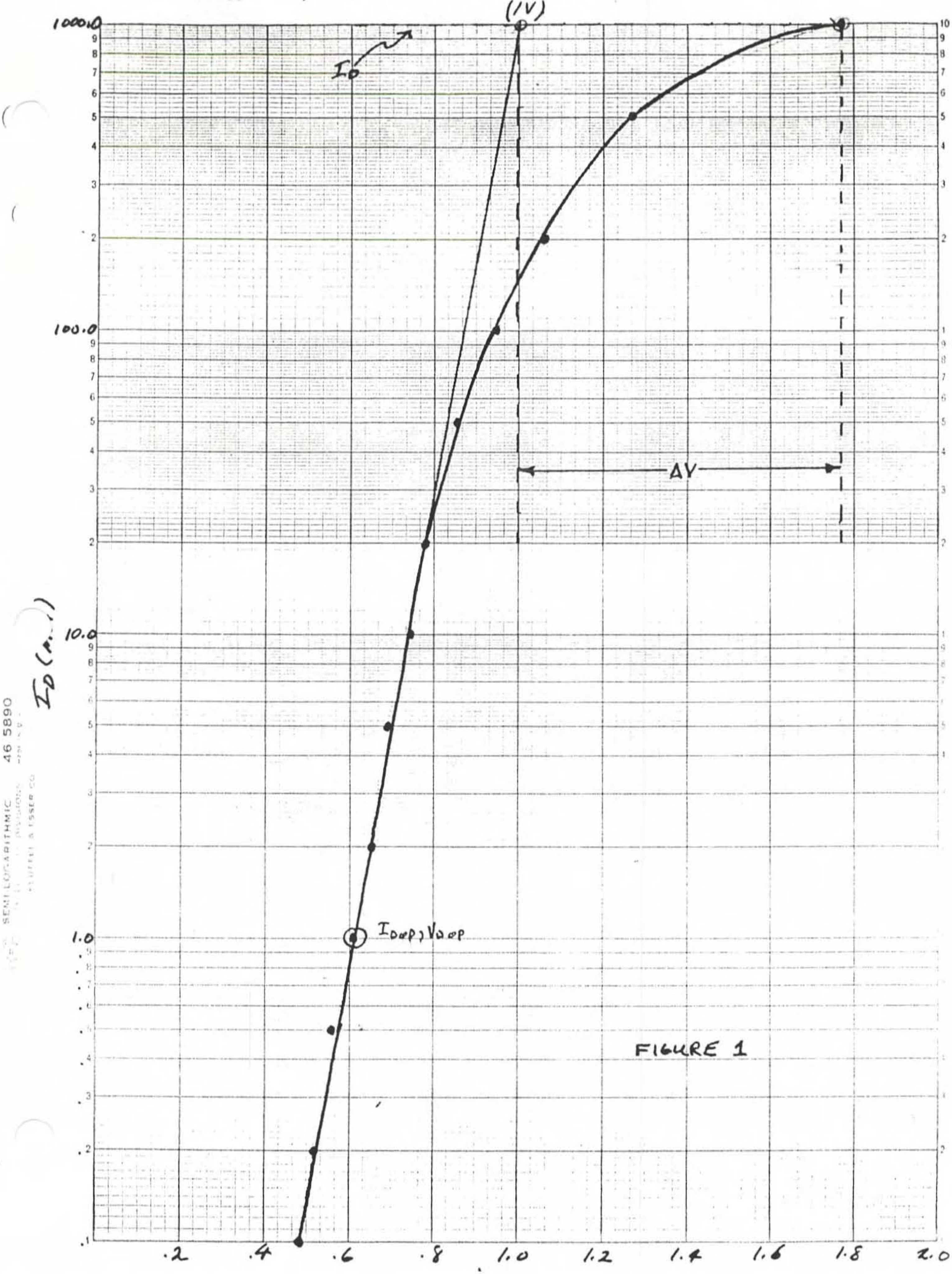
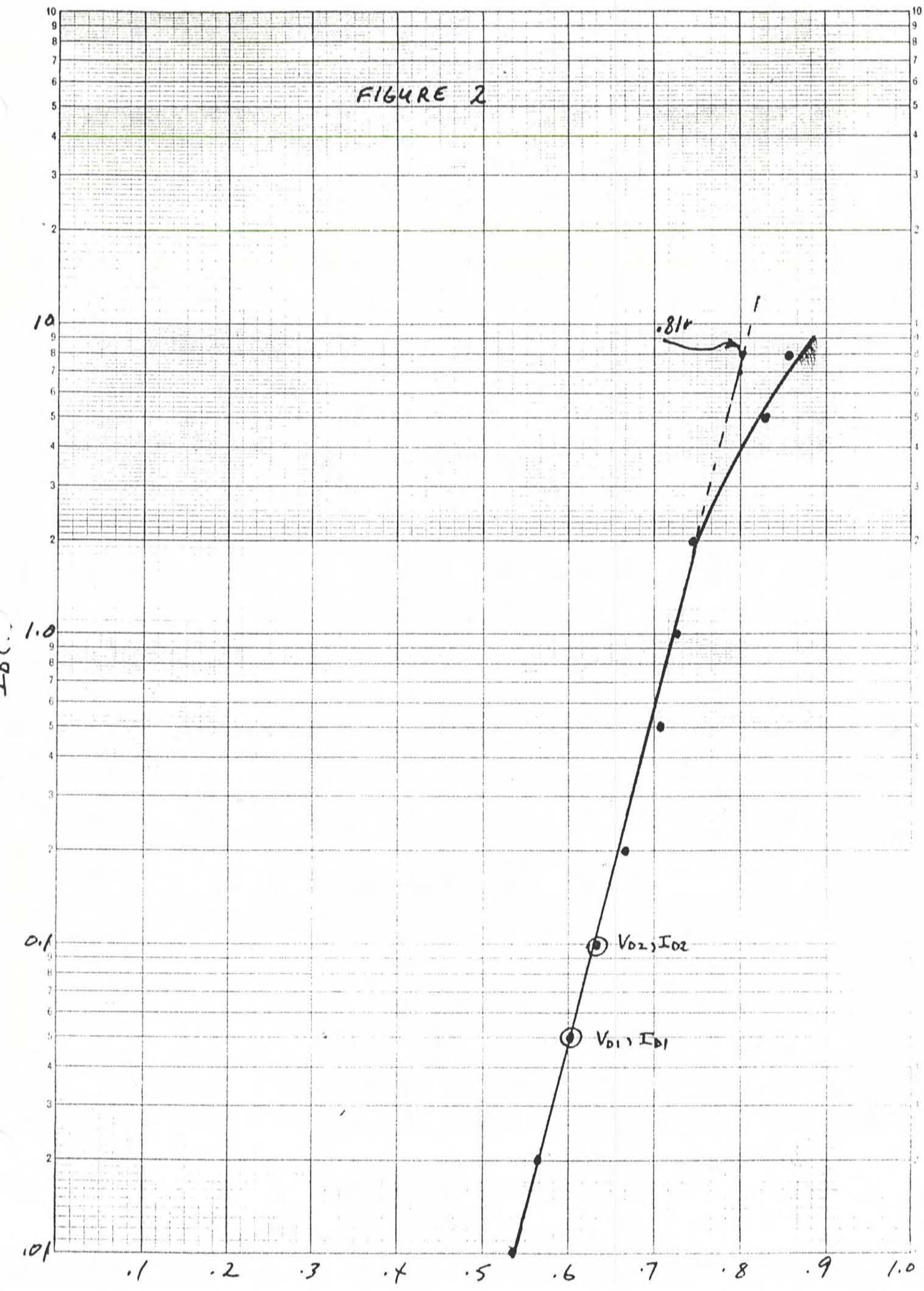


FIGURE 1

FORWARD BIAS CHARACTERISTIC 1N5811



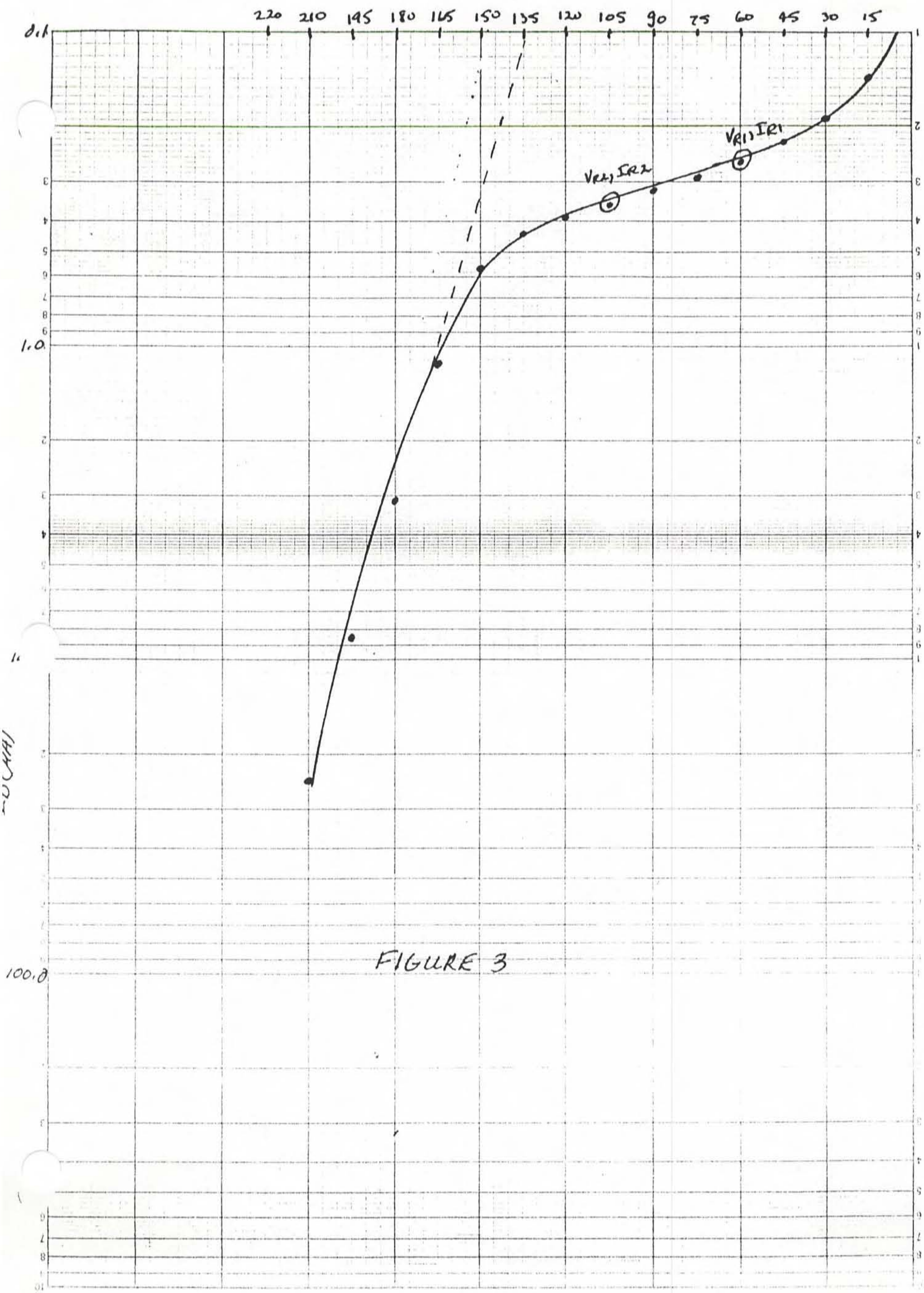

220
210
195
180
165
150
135
120
105
90
75
60
45
30
15
0.1
1.0
100.0
V_{R1}, I_{R1}
V_{R2}, I_{R2}

FIGURE 3

A. Determination of N

The analyst who wishes to simulate diode performance over several decades of current will realize that the ideal diode equation is not sufficient because most diodes do not have an ideal characteristic. The non-ideal region of the diode can be modeled as an emission constant (N) in the diode equation. N is determined by choosing two points from the straightest portion of the forward bias graph. These data points are then applied to the following equation:

N = VD2-VD1/(VT*ln(ID2/ID1))   Eq. #1

where Vt (thermal voltage) = KT = .025875 (at 300K).

K (Boltzman's Constant) = 8.62 x 10-5 ev/K
T (junction temperature in Kelvin)

The value of N typically lies between 1 and 2.

B. Determination of Is

The reverse saturation current, Is, is the amount of current a diode would conduct over a large range of reverse bias voltage. Ideally, this is the flat (constant current) region between initial reverse bias and breakdown. Practically, this region is not very flat so graphically obtaining this value could lead to erroneous results. Is is however obtained using the following equation which is based on a chosen operating point in the forward bias region (Pick a point on the linear portion of the forward characteristic). Typical values are on the order of 10-12 amperes, however, a variation in the range of several orders of magnitude is not uncommon. The Is parameter affects the shape of the forward characteristic, especially in the non-ideal region.

IS = ID/((exp(VD/(n*VT))-1)   Eq. #2

C. Determination of Rs

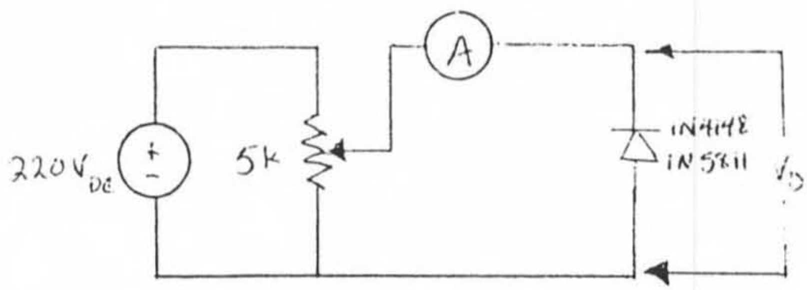
The parasitic or ohmic resistance Rs of a diode may be determined from the plot of forward current versus voltage. Two points are chosen from the high ohmic region of the graph. This is the curved region of the forward bias graph. One point is chosen directly on the curve. The second point is located at the intersection of the first points' current level and an extrapolation of the straight line region of the curve to a different voltage level. Both points should have the same current level in common but different voltage values. Rs can then be calculated as follows (refer to figure 1).

RS = ^VD/ID   Eq. #3

Typical values for Rs are around or under 1 Ohm. In Spice, RS is modeled as a linear resistance and will greatly affect the forward characteristic of ID vs. VD in the high ohmic region.

Reverse Characteristics

Reverse bias data for a diode is necessary to obtain two more SPICE parameters. These parameters are reverse breakdown voltage (BV) and reverse current at breakdown voltage (IBV). In general, fairly good values for BV and IBV may be obtained from device data sheets. These values may also be obtained experimentally. The following circuit may be used to measure reverse voltage versus current values:



The following data is an average of several measurements for the 1N4148 and 1N5811 diodes.

VD	ID(uA)
15	.14
30	.19
45	.227
60	.260
75	.290
90	.320
105	.352
120	.393
135	.440
150	.570
165	1.24
180	3.13
195	8.64
200	24.60

VD	ID(uA)
10	.01
20	.01
30	.01
40	.015
50	.02
60	.02
70	.02
80	.02
90	.02
100	.02
110	.025
120	.03
130	.05
140	.10
150	3.27

Figures 3 and 4 are the plots representing the collected data.

TYPICAL REVERSE CURRENT vs. VOLTAGE 1N4148

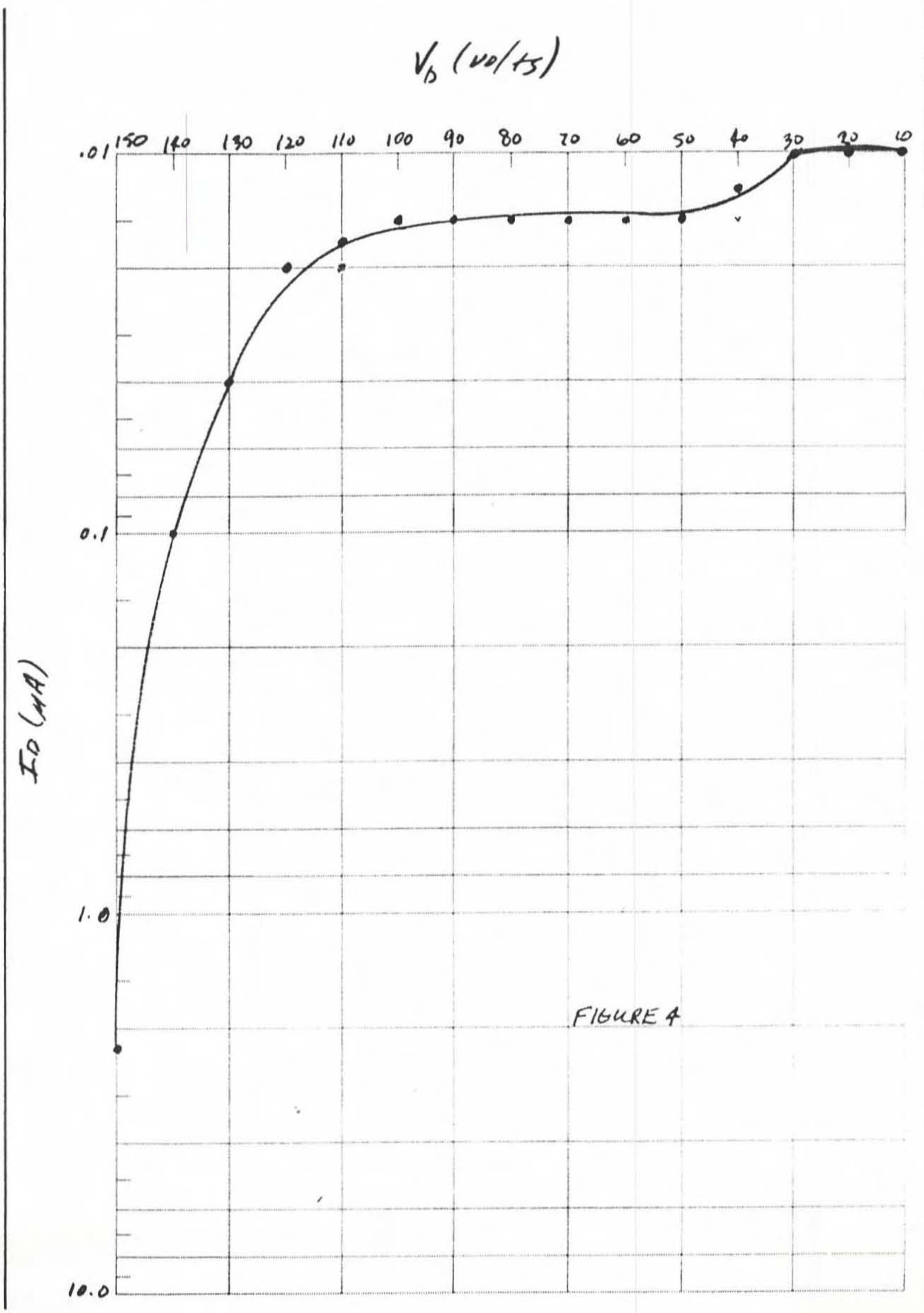


FIGURE 4

A. Determination of BV and IBV

From the graphs, BV may be obtained by extrapolating the straight line portion of the breakdown curve. IBV cannot accurately be obtained from the curve. However, knowledge of the maximum power dissipation rating and BV is enough to yield IBV.

As an example from the data sheets for the 1N5811:

Minimum Breakdown Voltage @ 100mA = 160V

Graphically the BV for the 1N5811 is 135V (see figure 3).

Depletion Region Capacitance

An analysis of the capacitance in this region usually referred to as junction capacitance yields not only the SPICE parameter CJO but also aids in the determination of junction potential (VJ) and grading coefficient (M).

By including the parameters CJO and M the accuracy of transient analysis is greatly improved.

Determination of CJO

Some data sheets specifically state CJO. When CJO is not available from the data sheets, an experimental approach must be used.

Through the use of an HP4271 LCR meter junction capacitance as a function of bias voltage data can be collected; specifically, the capacitance at zero bias. These values are typically in the pico-farad range. The default value for CJO is zero. Experience with Spice has shown failure in DC convergence and excessive iterations in transient analysis with CJO=0. It is recommended that a CJO value of at least 2 picofarads be used in all diode models.

Determination of VJ and M

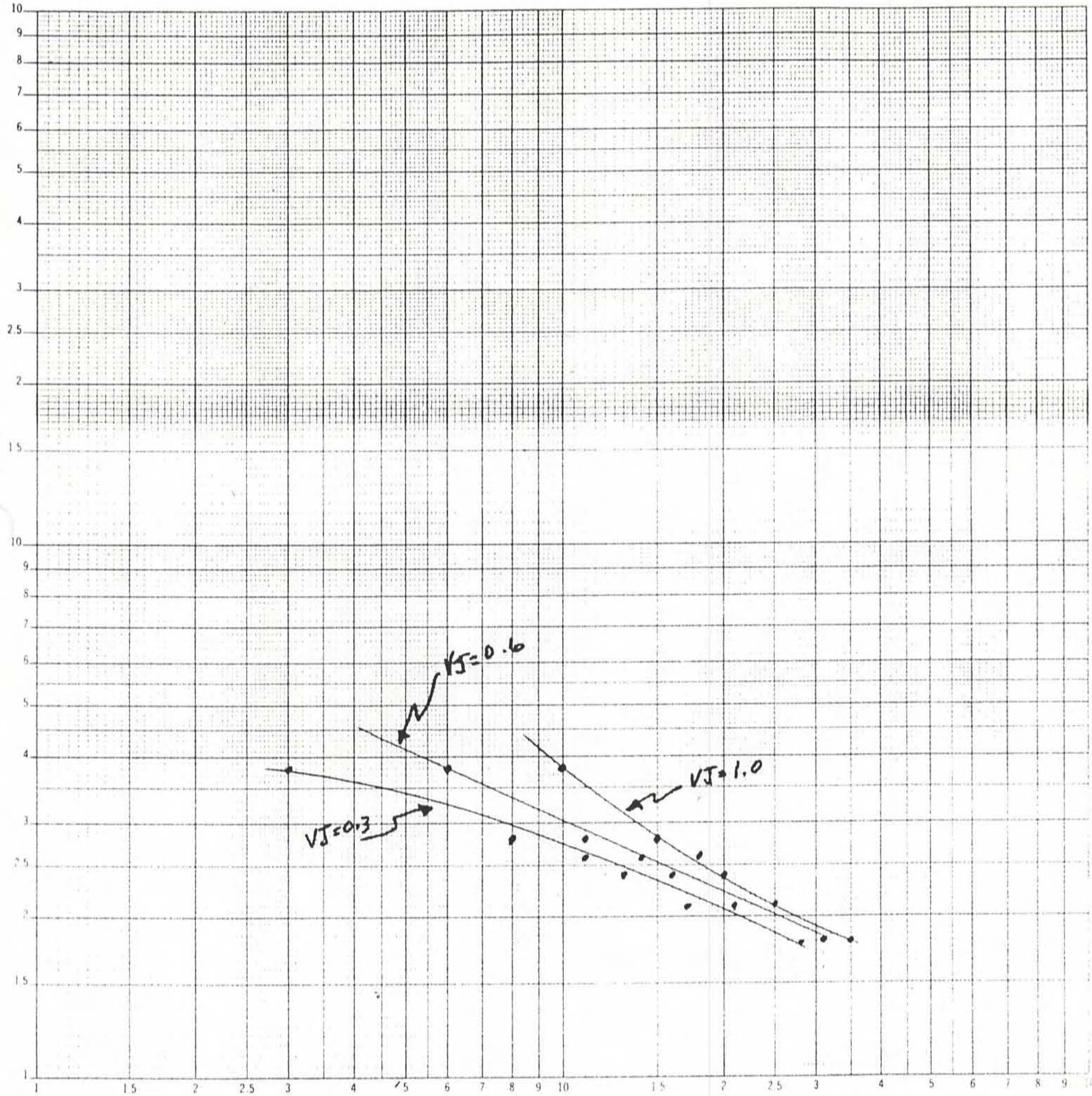
With the same test set up used to find CJO, obtain several more capacitance values in the reverse bias range.

Once this data is collected, determination of VJ and calculation of M can be accomplished through graphical techniques.

The technique involves first guessing a value for VJ (typically about 0.6V) and then plotting the resultant value of CJ as a function of (VJ-VD) on log-log paper. If the resulting curve is a straight line, the guess for VJ is correct. Should a concave down curve be obtained, decrease the value of the VJ guess and replot the graph.

REDUCED C-V PLOT
FOR THE 1N4148

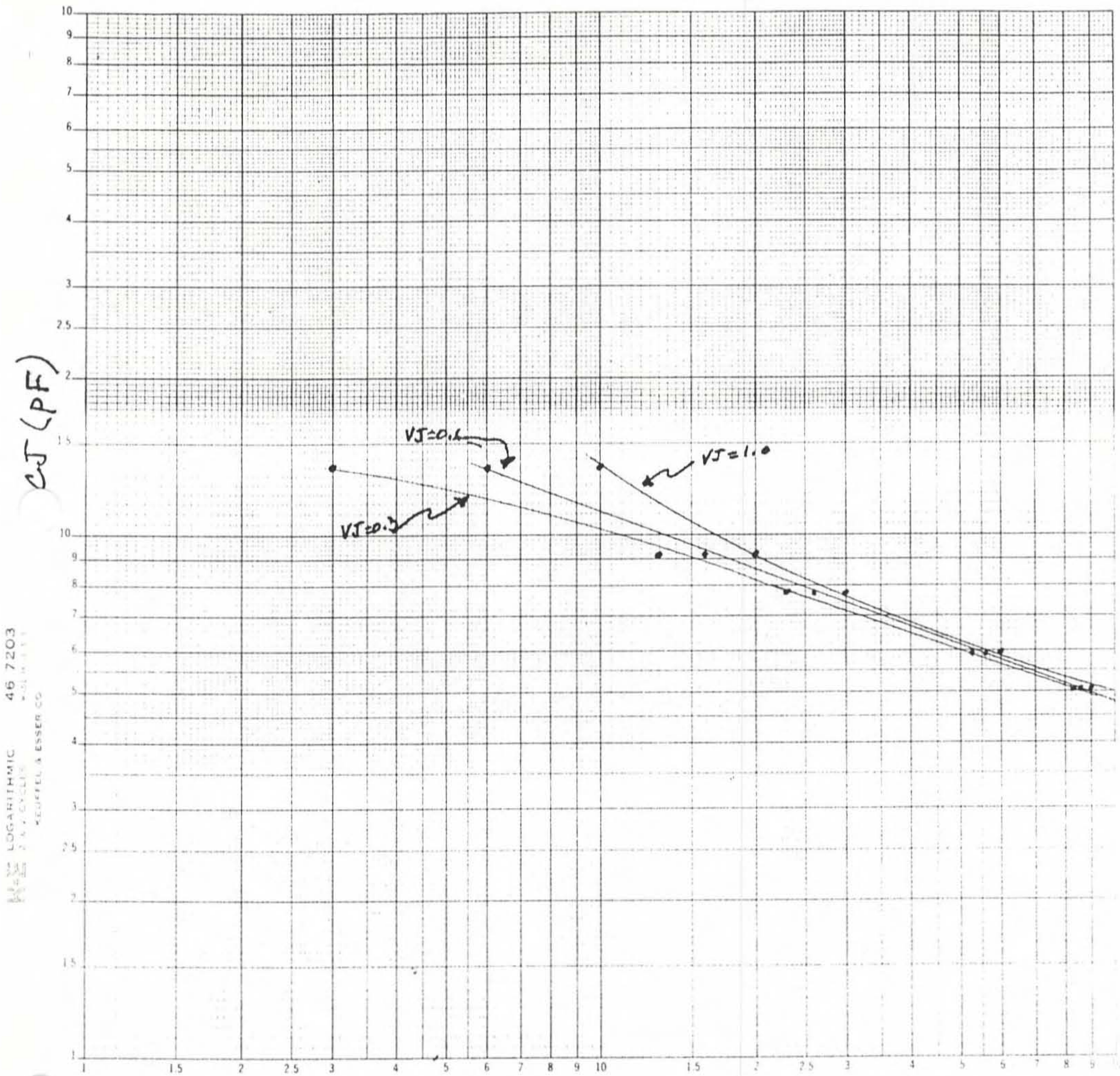
CJ (pF)



VJ – VD (volts)

FIGURE 5

REDUCED C-V PLOT
FOR THE IN5811



VJ-VD (volts)

FIGURE 6

Once a straight line is obtained, M is calculated as follows:

M = -[(log(Ct1)-log(Ct2))/(log(VD1)-log(VD2))]   Eq. #4

M is typically 0.333 (graded junction) and 0.5 (step junction) but may be much less for gold doped junctions.

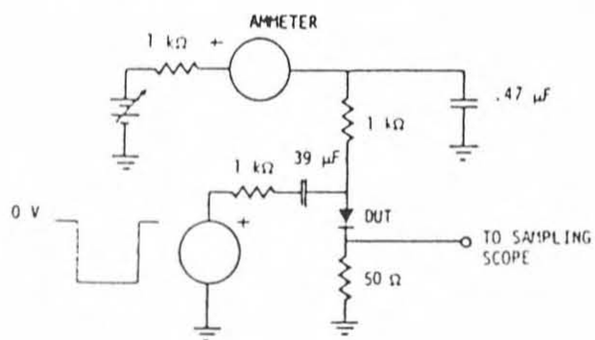
*For the 1N5811 and 1N4148 diodes, the following data was collected and compiled for the reduced C-V plot (see figures 5 and 6). The corresponding grading coefficient for each diode is also calculated.

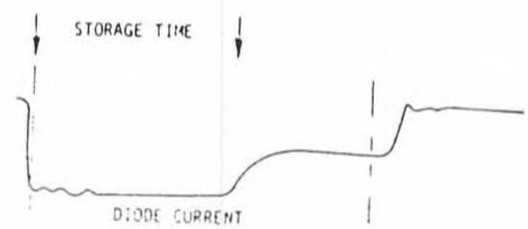
As can be seen by the graphs, both diodes exhibit junction potentials of 0.6V.

Transient Time

When a forward biased diode is abruptly reverse biased, there is a discrete amount of time which elapses before the diode is no longer conducting. This amount of time is called the reverse recovery time (trr).

Some data sheets indicate trr and the test values used to obtain it. When this data is not available, the following test set up may be employed.



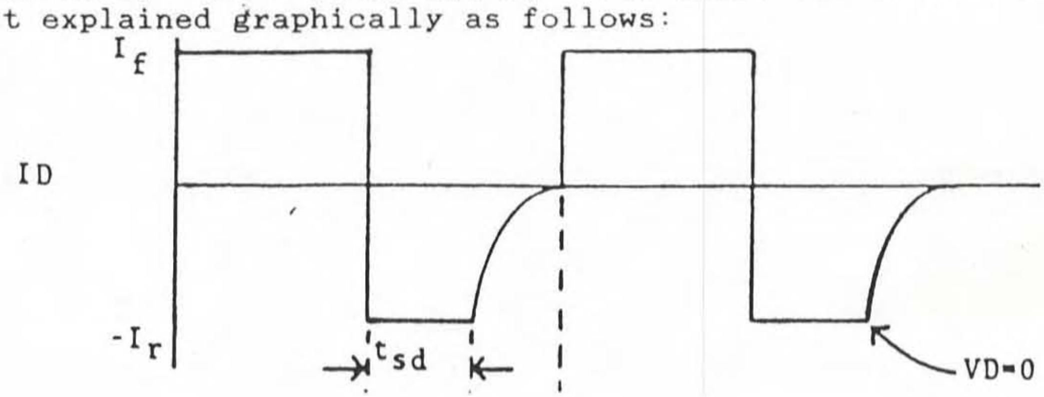


1N5811 Reverse Recovery Time Test Circuit

Figures 7 and 8 are the results of tests performed on the 1N5811 and 1N4148 using this circuit. Spice analysis of these circuits follow verifying the model against the laboratory data.

Determination of TT

From the data sheets for the 1N4148, a reverse recovery time trr is given as 5 ns at IF = IR = 10 mA and RL = 100 ohms. The reverse recovery time is best explained graphically as follows:



where t = -(RL+RS)*CJO*ln[.1IR/IF]   Eq. #5

and tsd is the storage delay time.

therefore trr = tsd + t   Eq. #6

Applying the equations to the 1N4148 data we find:

t = -(100+.78)(4pf)ln(.01) = .928uS   Eq. #7

therefore, tsd = trr -t
= 4.07ns

The SPICE parameter transient time (TT) is obtained through the following equation:

TT = tsd/(ln[1+ IF/IR])   Eq. #8

Experimentally, TT is found by extracting trr from the circuit discussed earlier. For the 1N5811 (see figure 6) trr is approximately 40 ns. Therefore:

t = -(100+.0052)(117pf)ln(.01) = 26.94ns

tsd = trr - t =13.06ns

TT = 13.06/ln(2) = 18.84ns

The transit time parameter, TT, may be left at the Spice default value of zero where reverse recovery time is not important in the particular circuit application.

Miscellaneous

SPICE models reverse breakdown with the parameters BV & IBV. If BV is not included in the model, the diode will not break down at any value of reverse voltage.

The Spice diode does not contain a leakage resistance. Incorporation of a fixed resistor in parallel with the diode has been found to improve the running time, and sometimes required to prevent termination of a run, where the diode is switching and especially where the diode is used as a ZENER diode. An arbitrary value of 100 MEG ohms may be used for many circuit applications. Otherwise, a value may be calculated from a data sheet reverse current vs. reverse voltage graph. Use the equation;

RC = VD/ID   Eq. #9

The data points used should be at least several volts away from the reverse breakdown point.

The SPICE parameters XTI & EG are used for temperature analysis the following values are typical for these parameters:

XTI = Saturation Current temperature exponent
3.0 for Junction diodes *
2.0 for Schottky-Barrier diodes

EG = Activation Energy in electron volts
1.11 for Si *
0.69 for Schottky-Barrier diodes
0.67 for Ge

* SPICE defaults to these values.

SPICE parameters flicker noise coefficient (KF), flicker noise exponent (AF) and coefficient for forward bias depletion capacitance are not covered in this study.

Conclusions

When finding TT experimentally, great care must be taken when assembling a test set up. Using a copper clad breadboard is strongly recommended. Also needed is a pulse generator which has both a fast transition time and an output amplitude around 10V. The faster and cleaner that your input pulse is, the better the accuracy of your final results.

When at all possible, extraction of data from the manufacturers data sheets is recommended since this data is a mean over a large number of components and will be able to yield either a MIN, MAX, or TYPICAL model depending on the data used.

1N4148 CALCULATIONS

From non-ideal region

```
ID1 = .1 mA @ .4877V
ID2 =  2 mA @ .6402
                N = (VD2-VD1)/(Vt(ln(ID2/ID1)))
                  = (.6402-.4877)/(.026(ln(2/.1))) = 1.9674

               IS = ID1/[exp(VD1/(N(Vt)) - 1]
                  = .001/[exp(.6037/(.026(1.9674)) - 1] = 7.0746E-9 A
```

From Ohmic Region

```
               RS = dV/ID3      ID3 = 1A @ 1.78V
                                Straight Extrapolated V = 1V
                  = (1.78 - 1)/1 = .78 ohms

                t = -RC(ln(.1)) = -(100)(4PF)(ln(.1)) = 9.21E-10 Sec

              tsd = trr - t = 7.079 NSec

              trr = 8 NSec

               TT = tsd/ln(2) = 1.0213E-8 Sec
```

1N5811 Calculations

From Non-Ideal Region

ID1 = .05 mA @ .6032V
ID2 = .1 mA @ .6344V

N = (VD2-VD1)/(Vt(ln(ID2/ID1))) = 1.7396

IS = ID1/[exp(VD1/N(Vt)) - 1] = 75.695 pA

RS = dV/ID3 8A @ .8514V
= .0052 ohms

t = -RC (ln(.1)) = -(100)(117PF)(ln(.1))
= 3.108E-8 Sec

trr = 40 NSec from Picture

tsd = trr - t = 40 - 31.08 = 8.915 NSec

TT = tsd/ln(2) = 12.86 Nsec

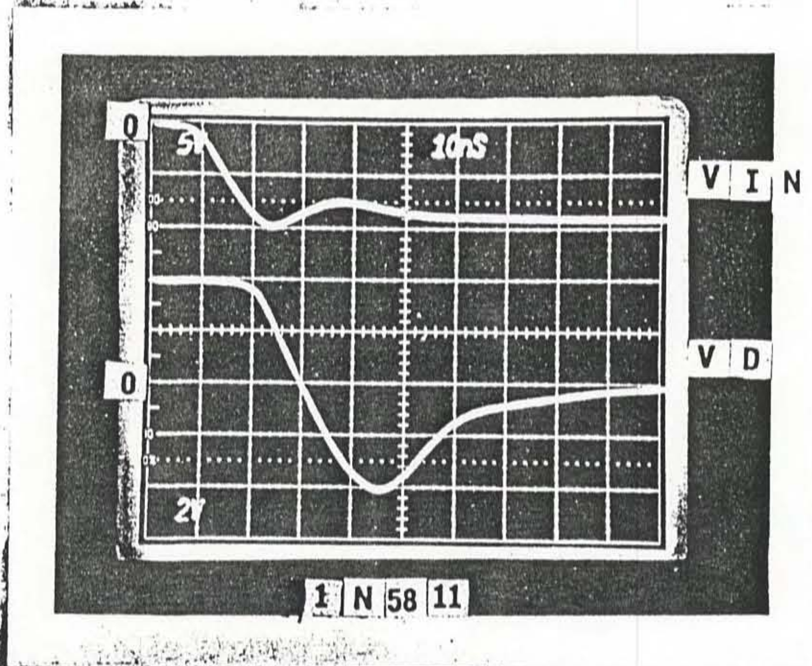


FIGURE 7

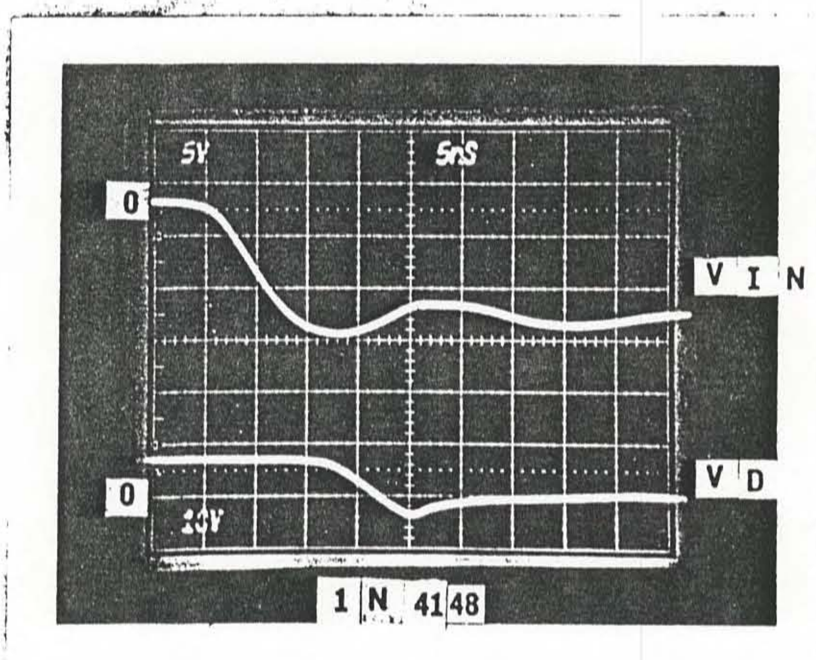
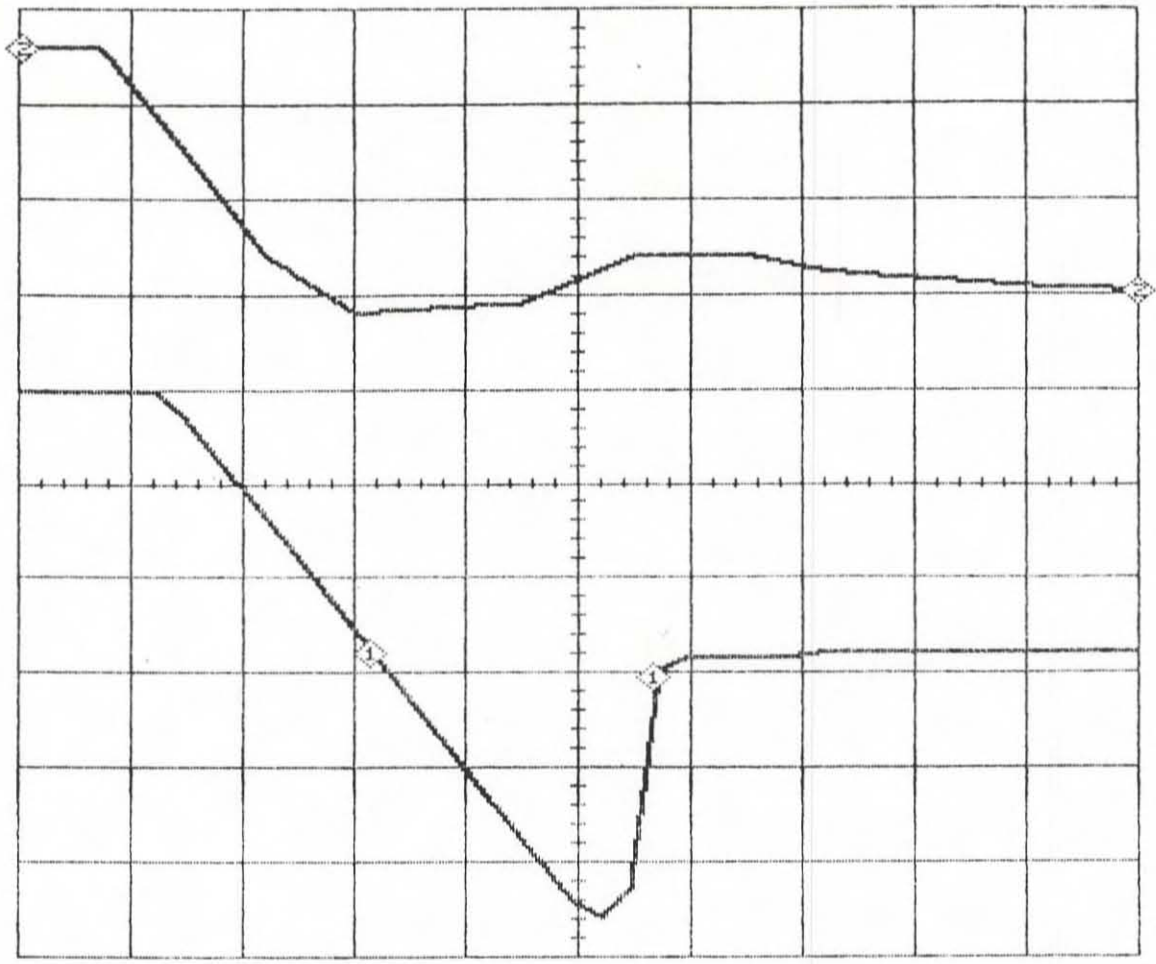


FIGURE 8

```
C>TYPE 1N4148.CIR
 1N4148 REVERSE RECOVERY TIME ANALYSIS
 .MODEL DIODE D(RS=.78 CJO=4PF IS=7.0746E-09 N=1.9674 VJ=.6V
 + TT=5.8847E-09 M=.448 BV=100V)
 D1 3 6 DIODE
 VR 5 0 PWL(0 0 5N 0 5.5N -0.5 6N -1.25 6.5N -2 7N -2.75 7.5N -3.5
 +8N -4.25 8.5N -5 9N -5.75 9.5N -6.5 10N -7.25 10.5N -8.0 11N -8.75
 +11.5N -9.5 12N -10.25 12.5N -11 13.5N -11.75 14.5N -12.5 15.5N -13.25
 +16.5N -14 24N -13.5 25N -13 26N -12.5 27N -12 28N -11.5 29N -11 34N -11
 +35N -11.25 37N -11.75 39N -12 42N -12.25 45N -12.5 48N -12.75 65N -13
 +70N -13.25 80N -13.5 90N -13.75 100N -14)
 VS 1 0 DC 17.5
 R1 1 2 100
 C1 2 0 .47UF
 R2 2 3 100
 C2 3 5 .47UF
 VMD 6 7
 R6 7 0 100
 .TRAN .5NS 200NS
 .PRINT TRAN I(VMD) V(5)
 .OPTIONS LIMPTS = 500
 .END
C>
```

SPICE ANALYSIS OF 1N4148.OUT on 8-26-85 page 1

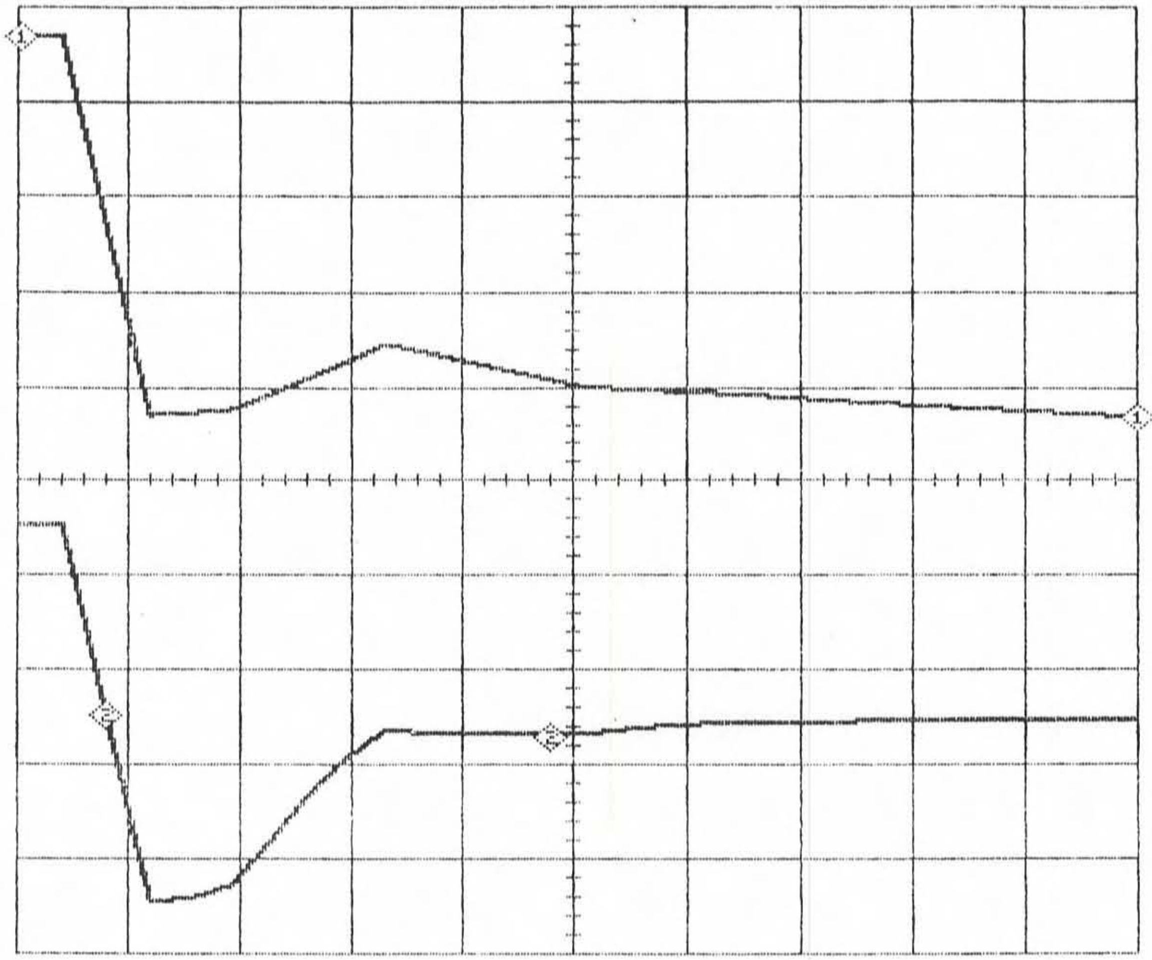


CH 1 I(VMD) vs TIME	CURSOR	LEFT	RIGHT	DIFFERENCE
YSCALE 20MA/DIV				
YZERO 36.0MA	VER	83.3UA	-5.31MA	-5.40MA
XSCALE 2NSEC/DIV				
XZERO 12.6NSEC	HOR	8.90NSEC	13.9NSEC	5.00NSEC

CH 2 V(5) vs TIME	CURSOR	LEFT	RIGHT	DIFFERENCE
YSCALE 5V/DIV				
YZERO -23.0 V	VER	0.00 V	-12.8 V	-12.8 V
XSCALE 5NSEC/DIV				
XZERO 26.5NSEC	HOR	1.50NSEC	51.5NSEC	50.0NSEC

```
C>TYPE 1N5811.CIR
 1N5811 REVERSE RECOVERY TIME ANALYSIS
 D1 3 6 DIODE
 .MODEL DIODE D(N=1.7396 RS=.0052 CJO=135PF IS=75.695E-12 VJ=.6V
 + M=.376 BV=160V IBV=100UA TT=12.86NS)
 VR 5 0 PWL(0 0 5N 0 5.5N -.5 6N -1 6.5N -1.5 7N -2 7.5N -2.5
 +8N -3  8.5N -3.5 9N -4 9.5N -4.5 10N -5 10.5N -5.5 11N -6 11.5N
 +-6.5 12N -7 12.5N -7.5 13N -8 20N -7.9 21N -7.8 22N -7.7 23N -7.6 24N -7.5
 +25N -7.4 26N -7.3 27N -7.2 28N -7.1 29N -7.0 30N -6.9 31N -6.8 32N -6.7
 +33N -6.6 34N -6.5 36N -6.6 38N -6.7 40N -6.8 42N -6.9 44N -7 46N -7.1
 +48N -7.2 50N -7.3 52N -7.4 60N -7.5 68N -7.6 74N -7.7 82N -7.8 90N -7.9
 +98N -8)
 VS 1 0 DC 13
 R1 1 2 100
 C1 2 0 .47UF
 R2 2 3 100
 C2 3 5 .47UF
 VMD 6 7
 R6 7 0 100
 .TRAN .5NS 200NS
 .PRINT TRAN I(VMD) V(5)
 .OPTIONS LIMPTS = 500
 .END
C>
```

SPICE ANALYSIS OF 1N5811.OUT on 8-26-85 page 1



CH 1 V(5) vs TIME	CURSOR	LEFT	RIGHT	DIFFERENCE
YSCALE 2V/DIV				
YZERO -9.40 V	VER	-509NV	-8.00 V	-8.00 V
XSCALE 10NSEC/DIV				
XZERO 51.0NSEC	HOR	1.00NSEC	101NSEC	100.0NSEC

CH 2 I(VMD) vs TIME	CURSOR	LEFT	RIGHT	DIFFERENCE
YSCALE 20MA/DIV				
YZERO 50.0MA	VER	396UA	-3.94MA	-4.33MA
XSCALE 10NSEC/DIV				
XZERO 51.0NSEC	HOR	9.00NSEC	49.0NSEC	40.0NSEC

SWITCHING AND GENERAL PURPOSE DIODES

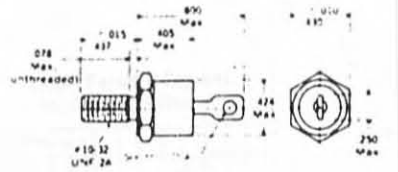
Type	Reverse Voltage	Forward Voltage	Reverse Recovery Time	Reverse Current @ 25°C	Junction Capacitance	Average Forward Current
1N456	30V	1.0 @ 40mA		25nA		90mA
1N457*	70V	1.0 @ 20mA		25nA		75mA
1N458*	150V	1.0 @ 7mA		25nA		55mA
1N459*	200V	1.0 @ 3mA		25nA		40mA
1N483B**	80V	1.0 @ 100mA		25nA		200mA
1N485B**	200V	1.0 @ 100mA		25nA		200mA
1N645***	270V	1.0 @ 400mA		25nA	20pF	400mA
1N914**	100V	1.0 @ 10mA	5nS	25nA	4pF	75mA
1N3064**	75V	1.0 @ 10mA	4nS	100nA	2pF	75mA
1N3070	200V	1.0 @ 100mA	50nS	100nA	5pF	100mA
1N3595***	150V	.83-1.0 @ 200mA	3μS	1nA	8pF	150mA
1N3600***	75V	.54-.62 @ 1mA	4nS	100nA	2.5pF	200mA
1N4148***	100V	1.0 @ 10mA	4nS	25nA	4pF	200mA
1N4149	75V	1.0 @ 10mA	4nS	25nA	2pF	200mA
1N4150***	75V	.54-.62 @ 1mA	4nS	100nA	2.5pF	200mA
1N4151	75V	1.0 @ 50mA	2nS	50nA	2pF	150mA
1N4152	40V	.49-.52 @ 0.1mA	2nS	50nA	2pF	150mA
1N4153***	75V	.49-.52 @ 0.1mA	2nS	50nA	2pF	150mA
1N4154	35V	1.0 @ 30mA	2nS	100nA	4pF	150mA
1N4305	75V	.5-.575 @ .25mA	2nS	100nA	2pF	150mA
1N4444	70V	.44-.55 @ .1mA		50nA	2pF	200mA
1N4446	75V	1.0 @ 20mA	4nS	25nA	4pF	150mA
1N4447	75V	1.0 @ 20mA	4nS	25nA	2pF	150mA
1N4448	75V	.62-.72 @ 5mA	4nS	25nA	4pF	150mA
1N4449	75V	.63-.73 @ 5mA	4nS	25nA	2pF	150mA
1N4450	40V	.42-.54 @ 0.1mA	4nS	50nA	4pF	200mA
1N4451	40V	.4-.5 @ 0.1mA	4nS	50nA	6pF	200mA
1N4452	40V	.42-.52 @ 0.1mA	50nS	50nA	30pF	200mA
1N4453	30V	.43-.55 @ 0.1mA		50nA	30pF	200mA
1N4454***	75V	1.0 @ 10mA	2nS	100nA	2pF	200mA
1N4500***	80V	.64-.72 @ 10mA	6nS	100nA	4pF	300mA
1N4607	85V	1.1 @ 400mA	10nS	100nA	4pF	400mA

*Available as JAN
**Available as JAN, JANTX
***Available as JAN, JANTX, JANTXV

XI

MECHANICAL SPECIFICATIONS

1N5812-1N5816



Part Identification: Type number printed on metal case.
Polarity: Cathode to stud end
Max. Weight: 7.0 Grams
Installation Precautions: Maximum unlubricated stud torque: 10 inch pounds
Thermal Resistance: 3.0°C/W

Dimensions in inches.

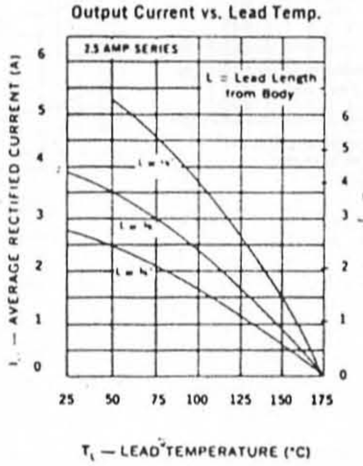
DO-4

ELECTRICAL SPECIFICATIONS (at 25°C unless noted)

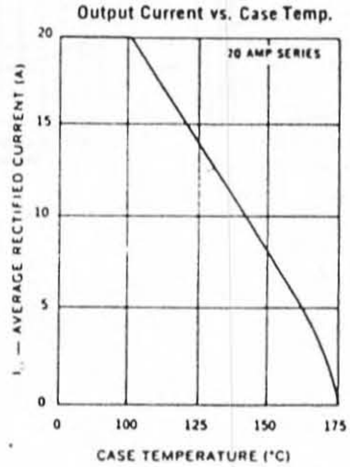
Type	PIV	Maximum Forward Voltage Drop*	Leakage Current @ PIV 25°C	Leakage Current @ PIV 100°C	Maximum Reverse Recovery Time I_f, I_r, I_{rr}	Typical Forward Recovery Time @ 1A Recover to 1V	Typical Forward Recovery Voltage @ 1A tr = 8ns	Typical Junction Capacitance @ −10V
1N5802 1N5803 1N5804 1N5805 1N5806	50V 75V 100V 125V 150V	.875 @ 1A	1μA	50μA	25ns, 0.5A-0.5A-0.05A	15ns	1.5V	15pf
1N5807 1N5808 1N5809 1N5810 1N5811	50V 75V 100V 125V 150V	.875 @ 4A	5μA	150μA	30ns, 1.0-1.0-0.1A	15ns	1.5V	45pf
1N5812 1N5813 1N5814 1N5815 1N5816	50V 75V 100V 125V 150V	.900 @ 10A	10μA	750μA	35ns, 1.0-1.0-0.1A	15ns	1.5V	200pf

*Pulse width = 250ms

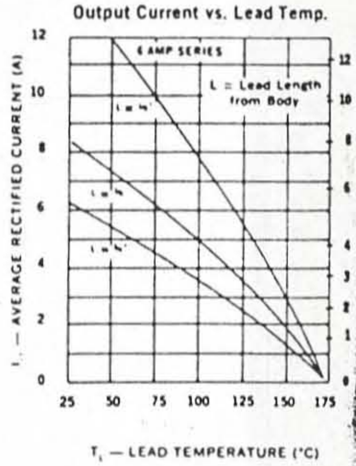
Output Current vs. Lead Temp.



Output Current vs. Case Temp.



Output Current vs. Lead Temp.



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