BJT Characterization Laboratory

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MicroE Webpage: http://www.microe.rit.edu**

OUTLINE

2N3904
BE Junction
BC Junction
IC-VCE Family of Curves
Beta at low, medium, high currents
SPICE Models
Temperature Effects

DEFINITIONS

Bipolar Junction Transistor - (BJT) Both holes and electrons participate in the conduction of current, hence the name bipolar.

Minority carrier - In a p-type semiconductor electrons are the minority carrier type, in an n-type semiconductor holes are the minority carrier type.

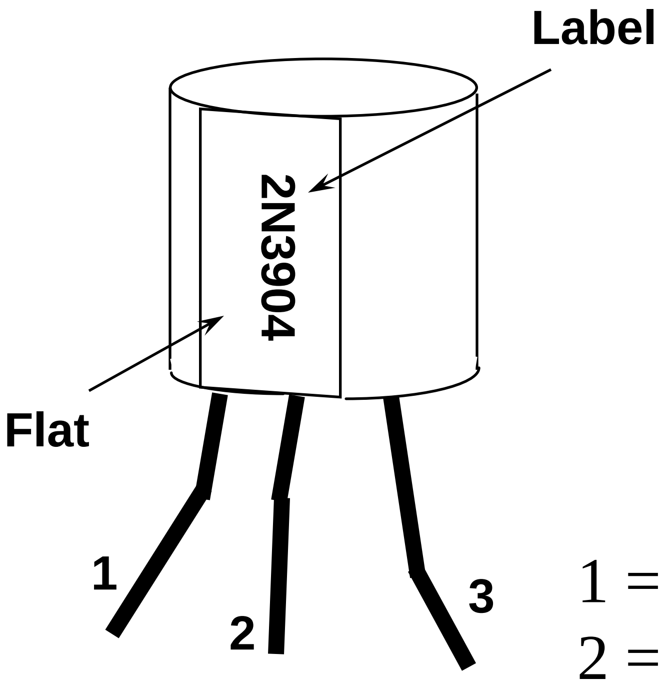
Emitter - Emits minority carriers into the base region of a BJT. For example, in an NPN BJT the n-type emitter, emits electrons into the p-type base. The emitter usually has the highest doping levels of the three regions of a BJT.

Base - Thin region which is used to control the flow of minority carriers from the emitter to the collector

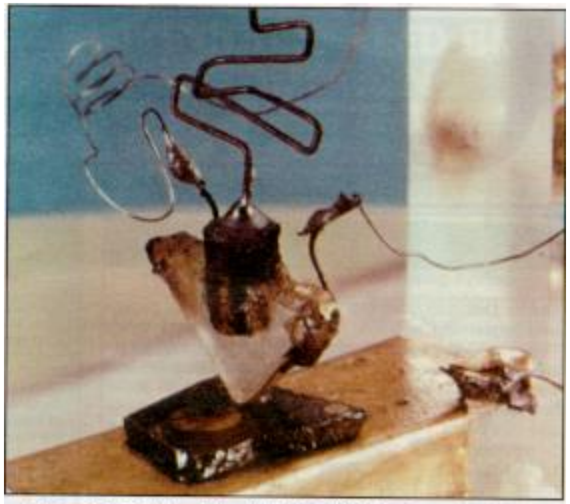
Collector -Collects the minority carriers that make it through the base from the emitter. The collector usually has the lightest doping concentrations of the three regions.

DC Beta (β_{dc}) - The ratio of the collector current to the base current. $\beta_{dc} = I_C / I_B$
AC Beta (β_{ac}) - The ratio of the change in the collector current to the change in the base current. $\beta_{ac} = \Delta I_C / \Delta I_B$

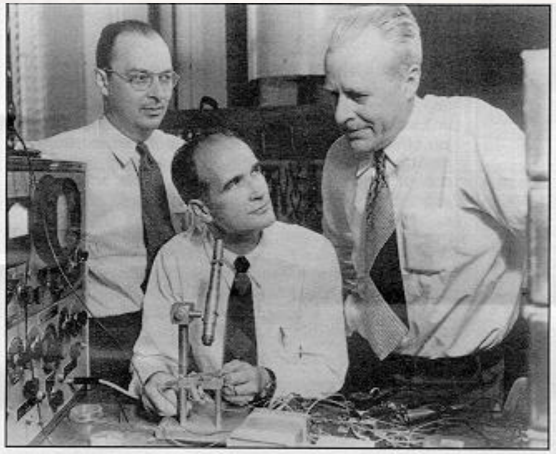
BJT - BIPOLAR JUNCTION TRANSISTOR



1 = Emitter
2 = Base
3 = Collector

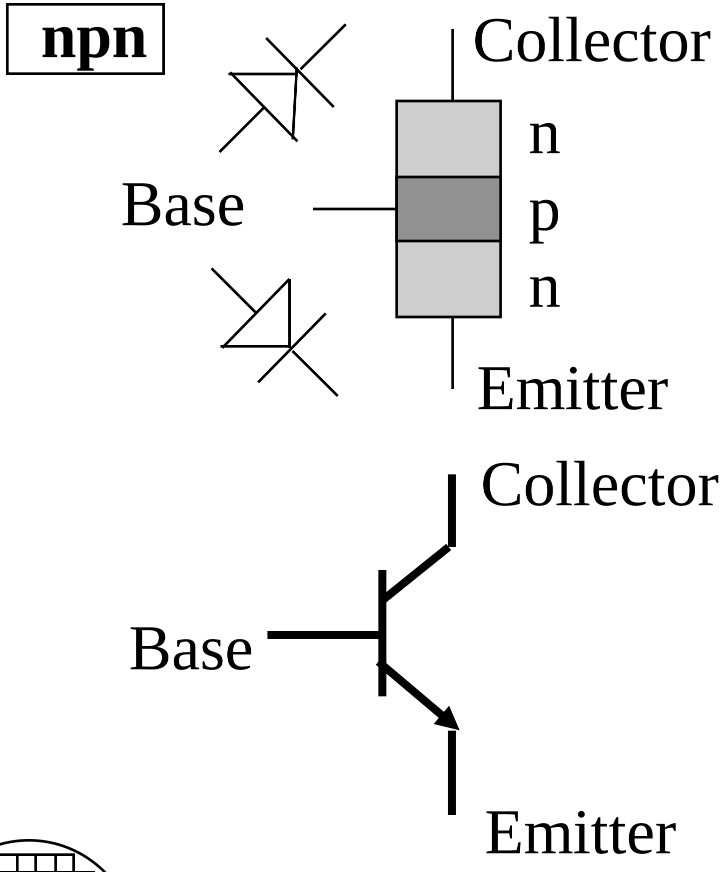


The world's first transistor, built at Bell Labs in December, 1947.



Transistor inventors (from left), Dr. Walter Brattain, Dr. William Shockley, and Dr. John Bardeen.

SCHEMATIC SYMBOLS



npn

Collector

n

p

n

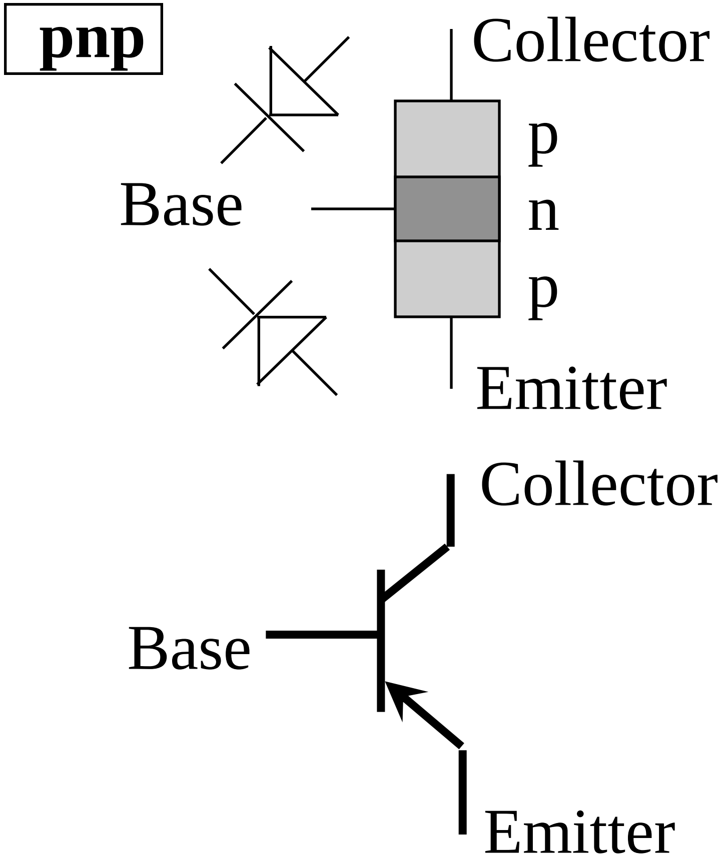
Base

Emitter

Collector

Base

Emitter



pnp

Collector

p

n

p

Base

Emitter

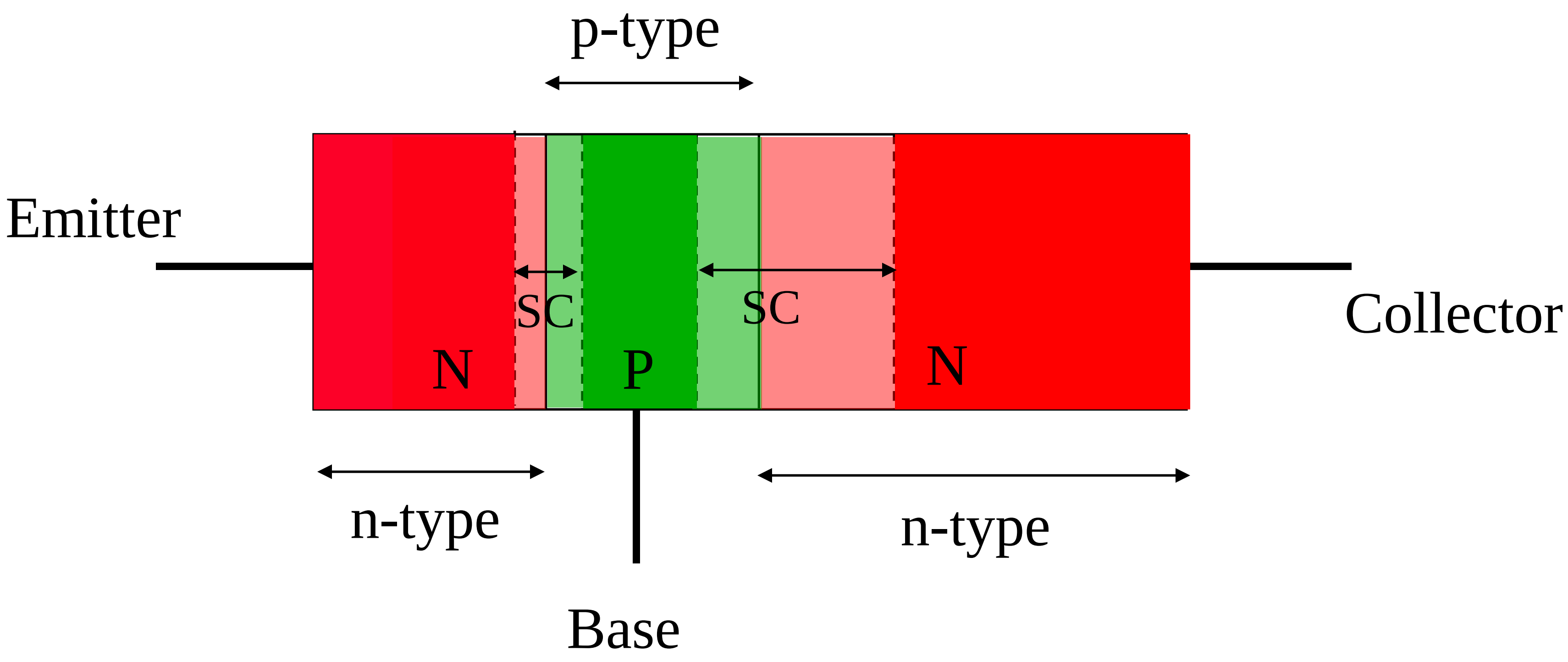
Collector

Base

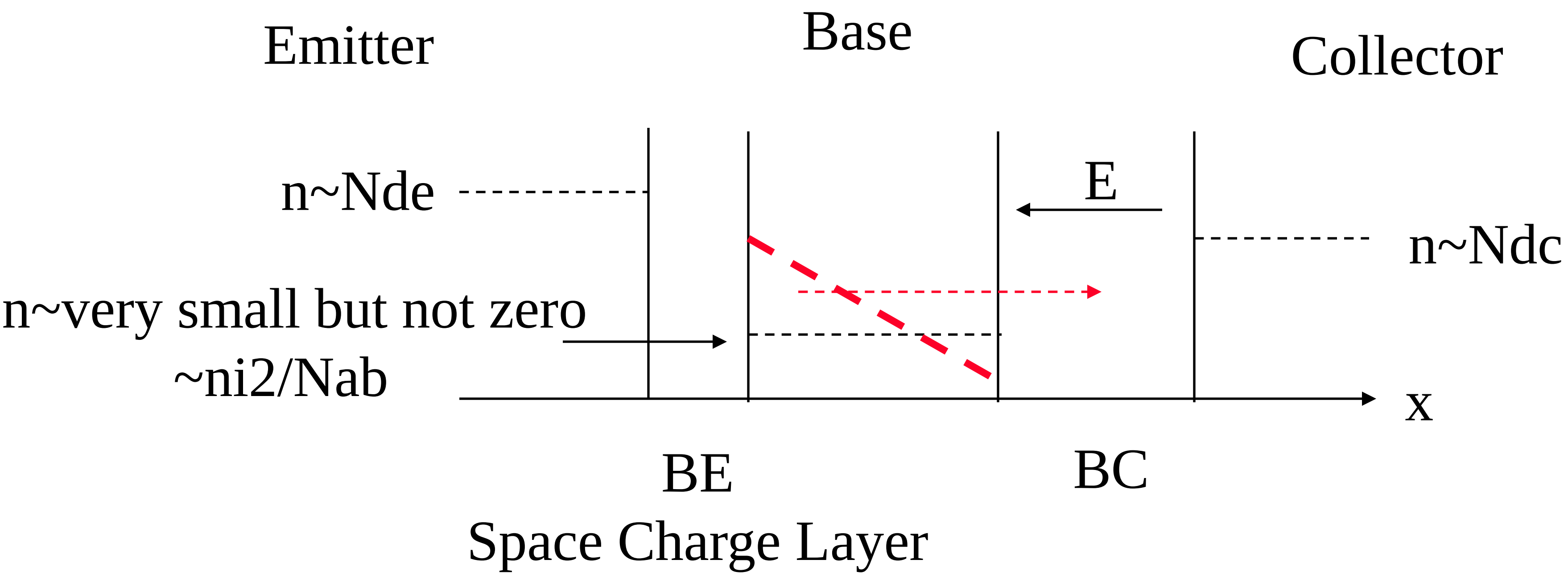
Emitter

The arrow on the emitter is in the direction that current will flow in the Base Emitter pn junction

IDEALIZED STRUCTURE



ELECTRON CONCENTRATIONS IN AN NPN BJT



Emitter

Base

Collector

n~Nde

E

n~Ndc

n~very small but not zero

~ni2/Nab

x

BE

BC

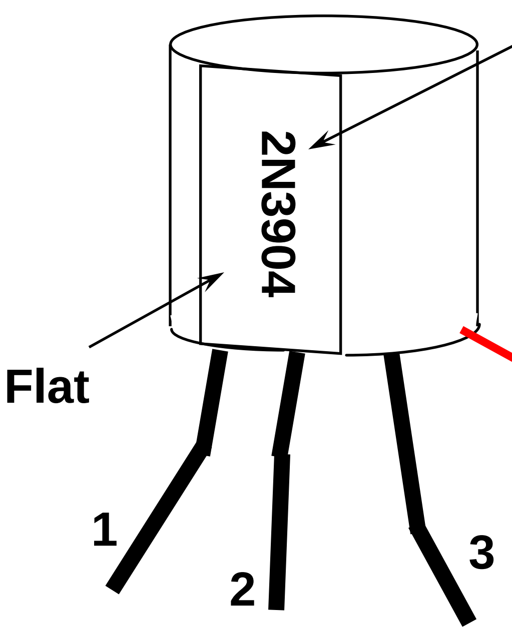
Space Charge Layer

With the B-E junction forward biased, and B-C junction reverse biased. There is a concentration gradient in the base that forces electrons to flow toward the collector.

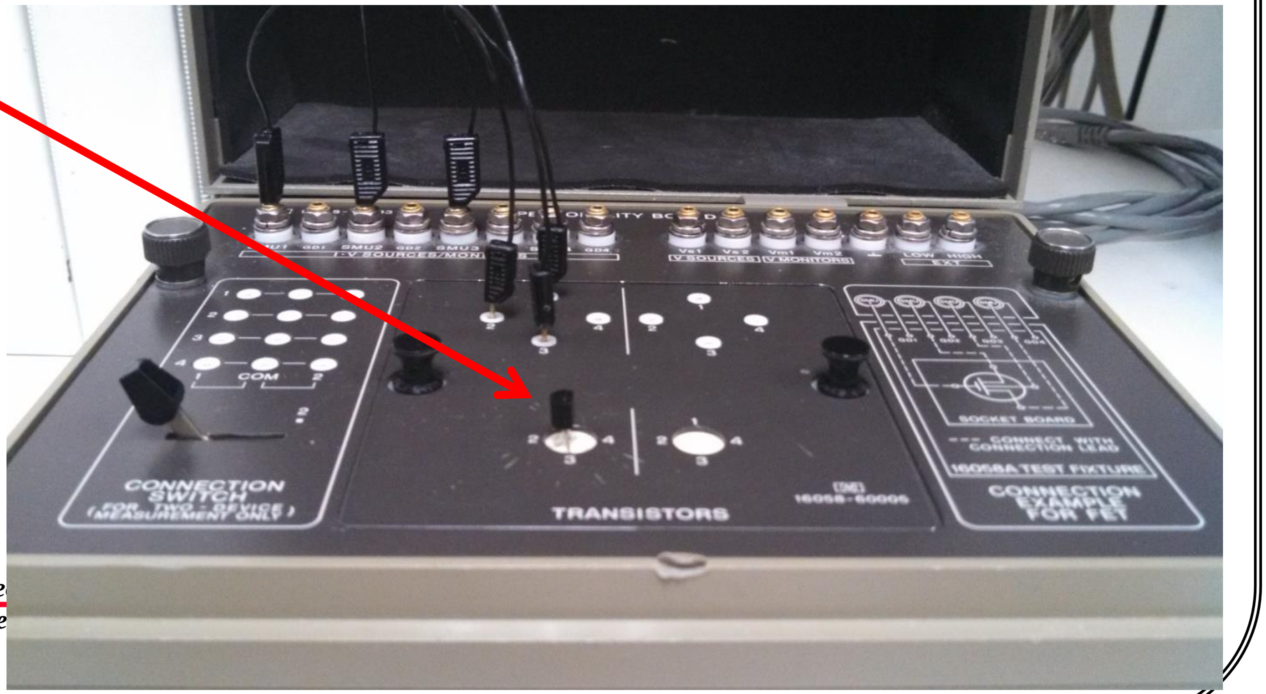
COMMENTS

1. The concentration of electrons in n-type silicon is ~ doping concentration in that region.
2. In p-type silicon the number of electrons is almost zero
3. A forward biased pn junction means more carriers of both types can cross the potential barrier. So a forward biased base-emitter junction (in an npn BJT) means more electrons on the base side than in equilibrium (no bias).
4. A reverse biased pn junction means less carriers of both types can cross the potential barrier. So a reverse biased base-collector junction (in an npn BJT) means less electrons on the base side than in equilibrium (no bias). Even closer to zero electrons in p-type base at the edge of the B-C space charge layer.
5. The base is so narrow that few electrons are lost as they diffuse across the base width. Diffusion is driven by a concentration gradient. So electrons move towards the collector and current flows in the opposite direction.

2N3904

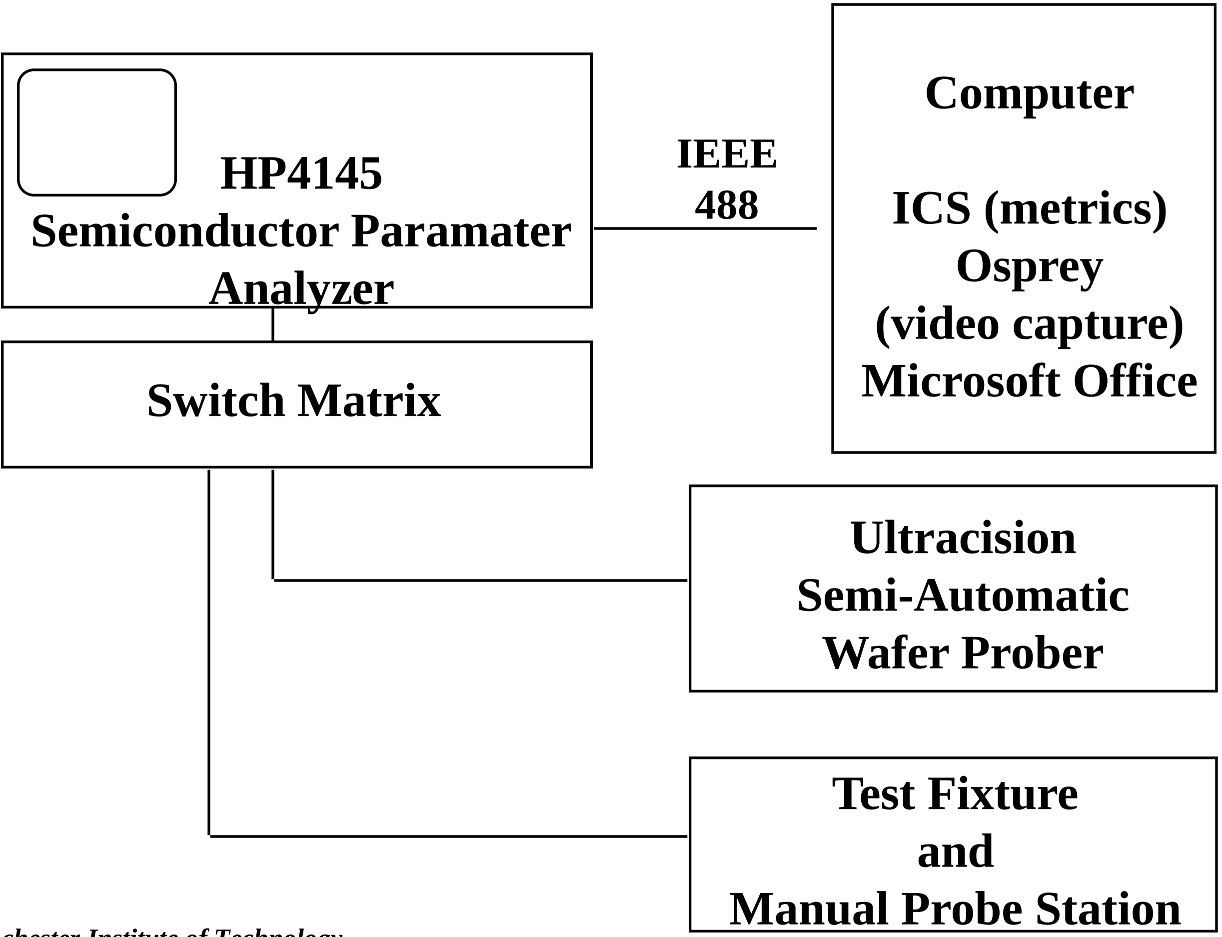


Test Fixture



HP4145B SEMICONDUCTOR PARAMETER ANALYZER

TEST EQUIPMENT



HP4145
Semiconductor Paramater Analyzer

IEEE 488

Computer

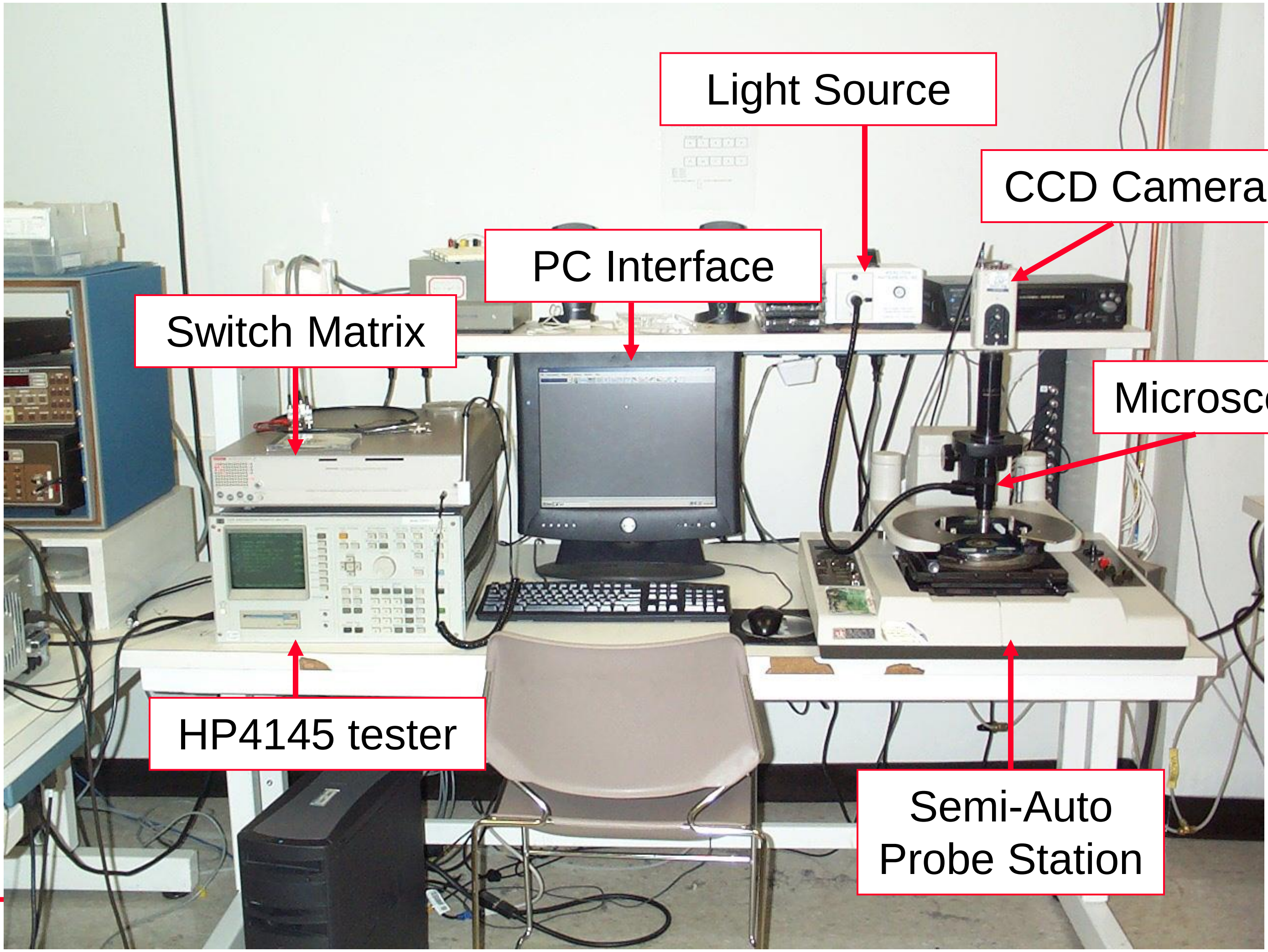
ICS (metrics)
Osprey (video capture)
Microsoft Office

Switch Matrix

Ultracision Semi-Automatic Wafer Prober

Test Fixture and Manual Probe Station

TEST STATION



OPERATION OF HP4145 AND SWITCH MATRIX

Turn on the HP4145, Switch Matrix, and PC
Select ICS icon on the desktop (close and message window)
Click on GPIB icon on the top of the screen select NI-32Thunk
Click on Instrument icon and select HP4145
Click on device icon and select PN Diode or BJT
    Click on SMU1 then click on terminal (n-side of diode)
        set SMU1 to zero volts ground
    Click on SMU2 then click on terminal (p-side of diode)
        set SMU2 to sweep from -10 to 10 Volts, measure I and V
    Click on done
Click on measure button
Wait for data to graph then add cursors, lines, titles, source conditions

2N3904 DATA SHEET

FAIRCHILD
SEMICONDUCTOR ™

2N3904 / MMBT3904 / PZT3904

2N3904 **MMBT3904** **PZT3904**

NPN General Purpose Amplifier

This device is designed as a general purpose amplifier and switch. The useful dynamic range extends to 100 mA as a switch and to 100 MHz as an amplifier.

Absolute Maximum Ratings*

T_A = 25°C unless otherwise noted

Symbol	Parameter	Value	Units
V_{CEO}	Collector-Emitter Voltage	40	V
V_{CBO}	Collector-Base Voltage	60	V
V_{EBO}	Emitter-Base Voltage	6.0	V
I_C	Collector Current - Continuous	200	mA
T_J, T_{stg}	Operating and Storage Junction Temperature Range	-55 to +150	°C

*These ratings are limiting values above which the serviceability of any semiconductor device may be impaired.

NOTES:
1) These ratings are based on a maximum junction temperature of 150 degrees C.
2) These are steady state limits. The factory should be consulted on applications involving pulsed or low duty cycle operations.

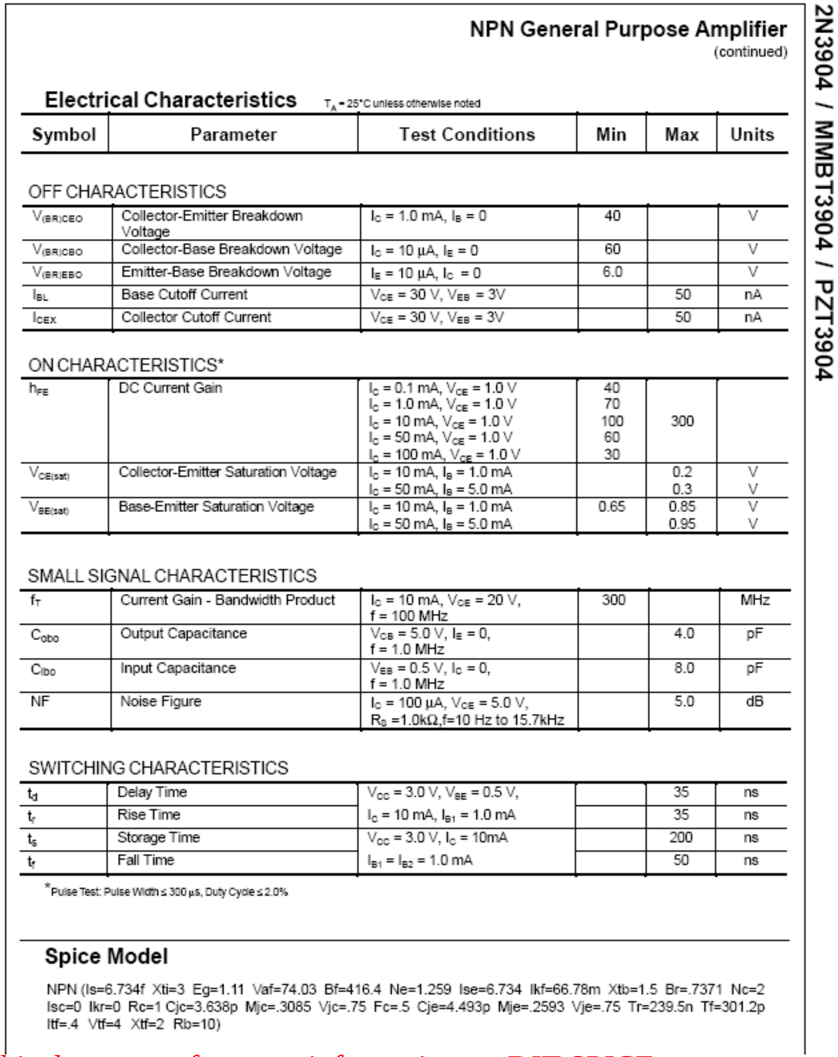
Thermal Characteristics

T_A = 25°C unless otherwise noted

Symbol	Characteristic	Max			Units
		2N3904	*MMBT3904	**PZT3904	
P_D	Total Device Dissipation Derate above 25°C	625 5.0	350 2.8	1,000 8.0	mW mW/°C
$R_{\theta JC}$	Thermal Resistance, Junction to Case	83.3			°C/W
$R_{\theta JA}$	Thermal Resistance, Junction to Ambient	200	357	125	°C/W

*Device mounted on FR-4 PCB 1.6" X 1.6" X 0.06."

**Device mounted on FR-4 PCB 36 mm X 18 mm X 1.5 mm; mounting pad for the collector lead min. 6 cm².



NPN General Purpose Amplifier
(continued)

2N3904 / MMBT3904 / PZT3904

Electrical Characteristics

T_A = 25°C unless otherwise noted

Symbol	Parameter	Test Conditions	Min	Max	Units
OFF CHARACTERISTICS					
$V_{(BR)CEO}$	Collector-Emitter Breakdown Voltage	I_C = 1.0 mA, I_B = 0	40		V
$V_{(BR)CBO}$	Collector-Base Breakdown Voltage	I_C = 10 µA, I_E = 0	60		V
$V_{(BR)EBO}$	Emitter-Base Breakdown Voltage	I_E = 10 µA, I_C = 0	6.0		V
I_{BL}	Base Cutoff Current	V_{CE} = 30 V, V_{EB} = 3V		50	nA
I_{CEX}	Collector Cutoff Current	V_{CE} = 30 V, V_{EB} = 3V		50	nA
ON CHARACTERISTICS*					
h_{FE}	DC Current Gain	I_C = 0.1 mA, V_{CE} = 1.0 V I_C = 1.0 mA, V_{CE} = 1.0 V I_C = 10 mA, V_{CE} = 1.0 V I_C = 50 mA, V_{CE} = 1.0 V I_C = 100 mA, V_{CE} = 1.0 V	40 70 100 60 30	300	
$V_{CE(sat)}$	Collector-Emitter Saturation Voltage	I_C = 10 mA, I_B = 1.0 mA I_C = 50 mA, I_B = 5.0 mA		0.2 0.3	V V
$V_{BE(sat)}$	Base-Emitter Saturation Voltage	I_C = 10 mA, I_B = 1.0 mA I_C = 50 mA, I_B = 5.0 mA	0.65	0.85 0.95	V V
SMALL SIGNAL CHARACTERISTICS					
f_T	Current Gain - Bandwidth Product	I_C = 10 mA, V_{CE} = 20 V, f = 100 MHz	300		MHz
C_{obo}	Output Capacitance	V_{CB} = 5.0 V, I_E = 0, f = 1.0 MHz		4.0	pF
C_{ibo}	Input Capacitance	V_{EB} = 0.5 V, I_C = 0, f = 1.0 MHz		8.0	pF
NF	Noise Figure	I_C = 100 µA, V_{CE} = 5.0 V, R_S =1.0kΩ,f=10 Hz to 15.7kHz		5.0	dB
SWITCHING CHARACTERISTICS					
t_d	Delay Time	V_{CC} = 3.0 V, V_{BE} = 0.5 V,		35	ns
t_r	Rise Time	I_C = 10 mA, I_{B1} = 1.0 mA		35	ns
t_s	Storage Time	V_{CC} = 3.0 V, I_C = 10mA		200	ns
t_f	Fall Time	I_{B1} = I_{B2} = 1.0 mA		50	ns

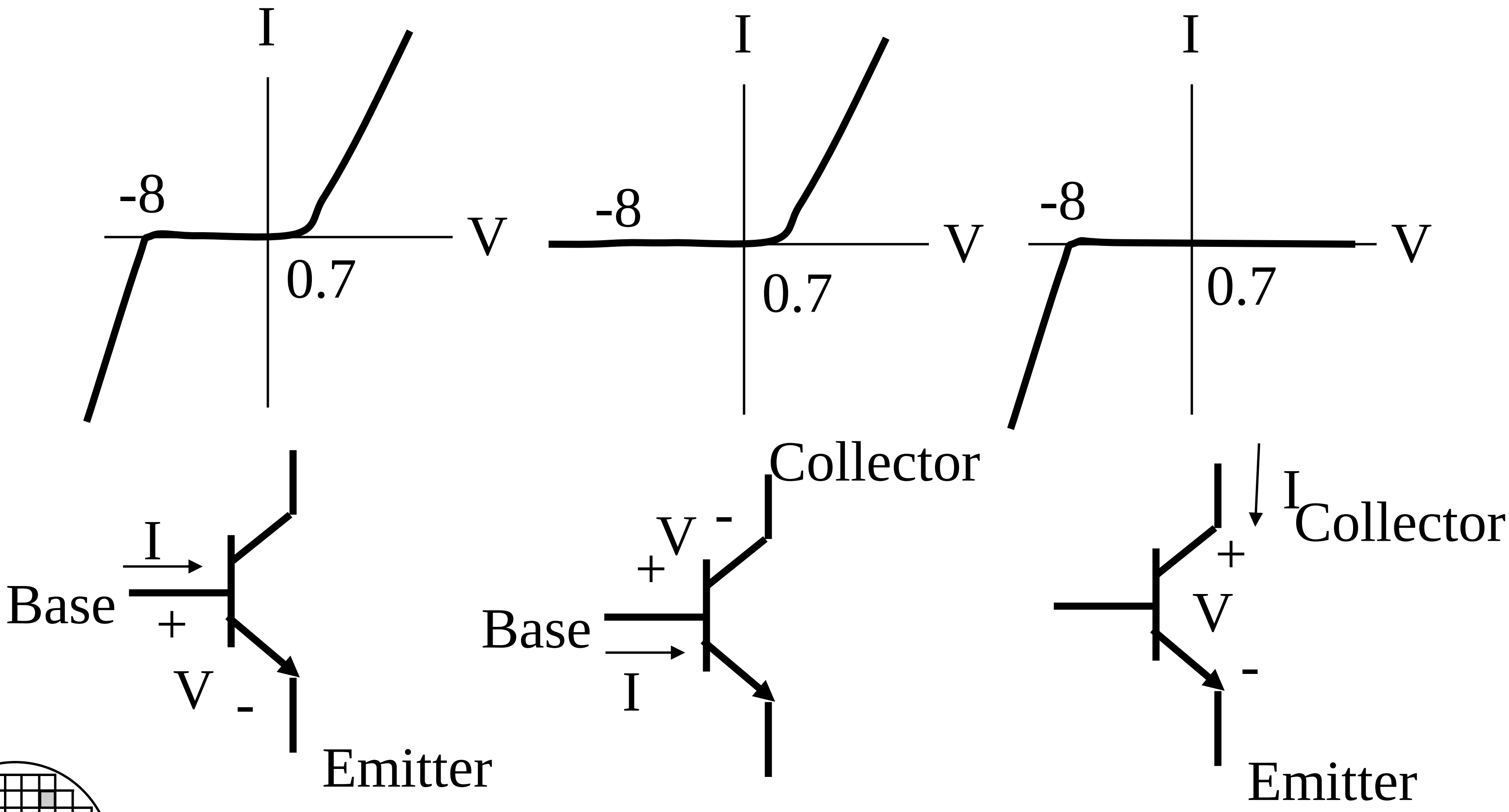
*Pulse Test: Pulse Width ≤ 300 µs, Duty Cycle ≤ 2.0%

Spice Model

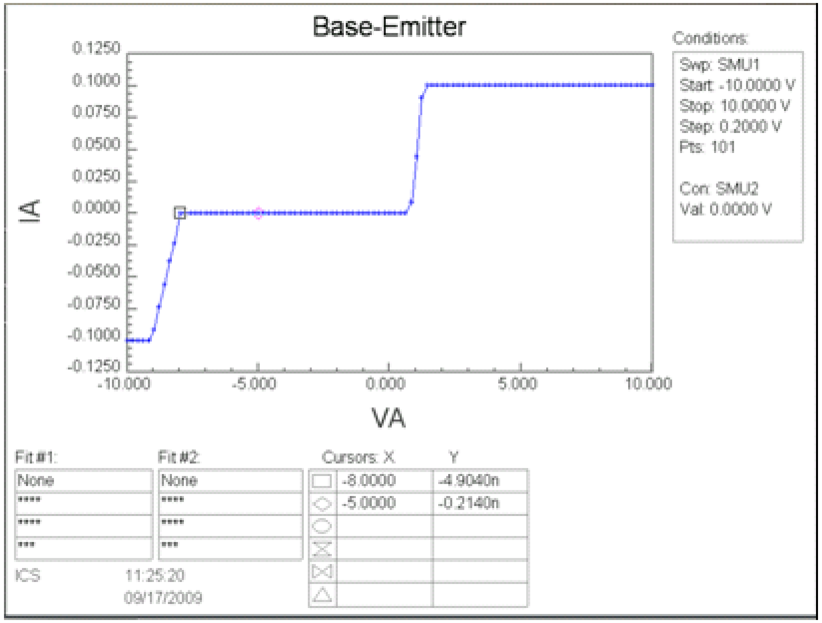
NPN (Is=6.734f Xti=3 Eg=1.11 Vaf=74.03 Bf=416.4 Ne=1.259 Ise=6.734 Ikf=66.78m Xtb=1.5 Br=.7371 Nc=2 Isc=0 Ikr=0 Rc=1 Cjc=3.638p Mjc=.3085 Vjc=.75 Fc=.5 Cje=4.493p Mje=.2593 Vje=.75 Tr=239.5n Tf=301.2p Itf=.4 Vtf=4 Xtf=2 Rb=10)

Note: see page 12-15 of this document for more information on BJT SPICE parameters

THEORETICAL BE JUNCTION, BC JUNCTION, CE



BE AND BC DIODE CHARACTERISTICS



Conditions:
Swp: SMU1
Start: -10.0000 V
Stop: 10.0000 V
Step: 0.2000 V
Pts: 101

Con: SMU2
Val: 0.0000 V

Fit #1:	Fit #2:
None	None
****	****
****	****
***	***

Cursors:	X	Y
□	-8.0000	-4.9040n
◇	-5.0000	-0.2140n
○		
⧗		
⋈		
△		

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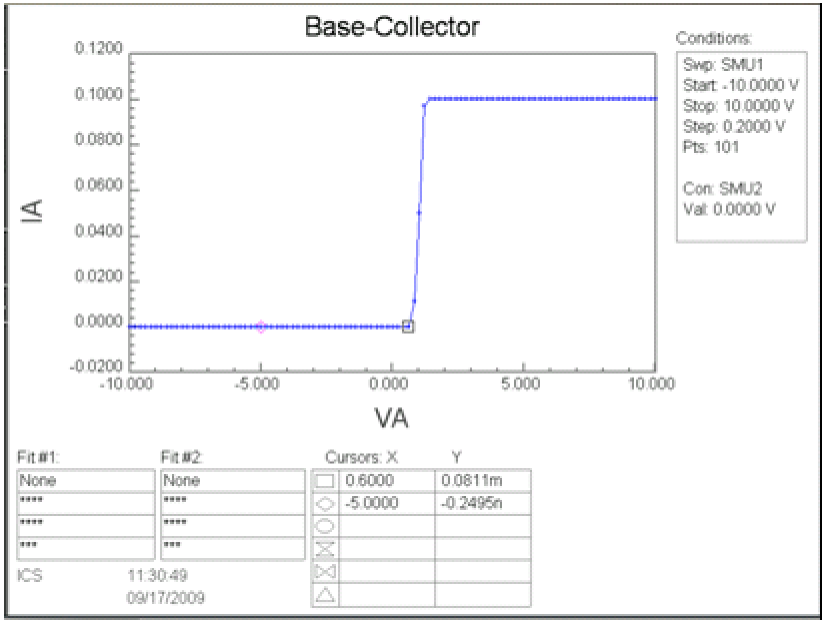

Conditions:
Swp: SMU1
Start: -10.0000 V
Stop: 10.0000 V
Step: 0.2000 V
Pts: 101

Con: SMU2
Val: 0.0000 V

Fit #1:	Fit #2:
None	None
****	****
****	****
***	***

Cursors:	X	Y
□	0.6000	0.0811m
◇	-5.0000	-0.2495n
○		
⧗		
⋈		
△		

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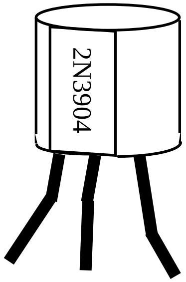
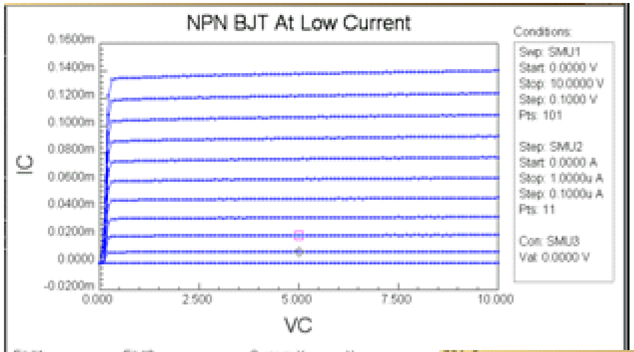
Identify BE junction, measure ISE and VBE. Identify BC junction and measure IS. Identify Base, Emitter, Collector leads and label on sketch.



BETA MEASURED FROM FAMILY OF CURVES



Conditions:
Swp: SMU1
Start: 0.0000 V
Stop: 10.0000 V
Step: 0.1000 V
Pts: 101

Step: SMU2
Start: 0.0000 A
Stop: 1.0000u A
Step: 0.1000u A
Pts: 11

Con: SMU3
Val: 0.0000 V

Fit #1:	Fit #2:
None	None
****	****
****	****
***	***

Cursors:	X	Y
□	5.0000	0.0196m
◇	5.0000	7.9684u
○		
⧖		
⋈		
△		

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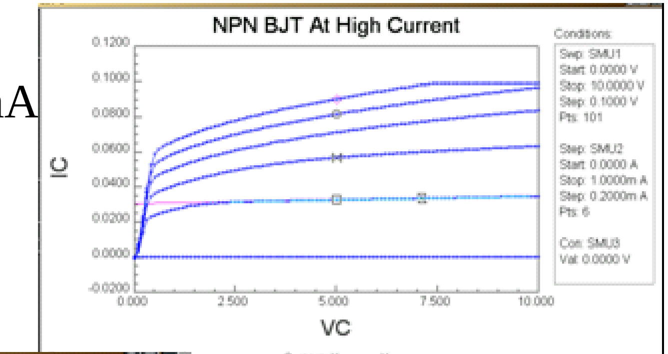
09/17/2009

Beta = 44 @ ~90mA
and Vce=5



Conditions:
Swp: SMU1
Start: 0.0000 V
Stop: 10.0000 V
Step: 0.1000 V
Pts: 101

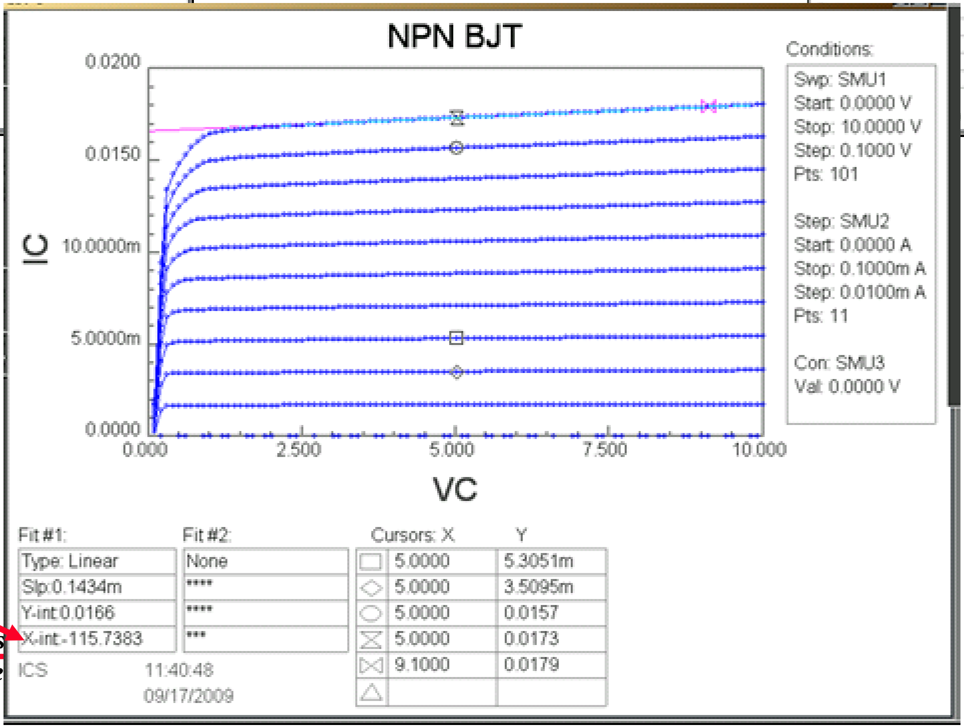
Step: SMU2
Start: 0.0000 A
Stop: 1.0000m A
Step: 0.2000m A
Pts: 6

Con: SMU3
Val: 0.0000 V

Cursors:	X	Y
□	5.0000	0.0325
◇	5.0000	0.0902
○	5.0000	0.0815
⧖	7.1000	0.0334
⋈	5.0000	0.0567
△		

Beta = 116 @
~0.02mA and Vce=5

Early Voltage is
measured to be 116
for IC ~ 15 mA



Conditions:
Swp: SMU1
Start: 0.0000 V
Stop: 10.0000 V
Step: 0.1000 V
Pts: 101

Step: SMU2
Start: 0.0000 A
Stop: 0.1000m A
Step: 0.0100m A
Pts: 11

Con: SMU3
Val: 0.0000 V

Fit #1:	Fit #2:
Type: Linear	None
Slp:0.1434m	****
Y-int:0.0166	****
X-int:-115.7383	***

Cursors:	X	Y
□	5.0000	5.3051m
◇	5.0000	3.5095m
○	5.0000	0.0157
⧖	5.0000	0.0173
⋈	9.1000	0.0179
△		

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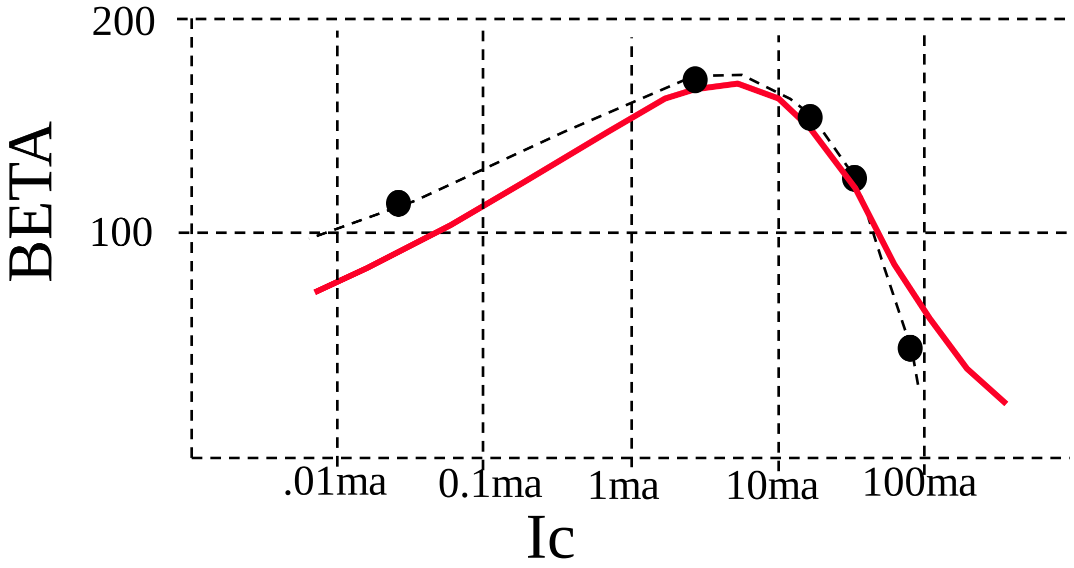
09/17/2009

Beta = 121 @
~40mA and Vce=5

Beta = 160 @
~15mA and Vce=5

Beta = 180 @ ~5mA
and Vce=5

BETA VS IC – 2N3904

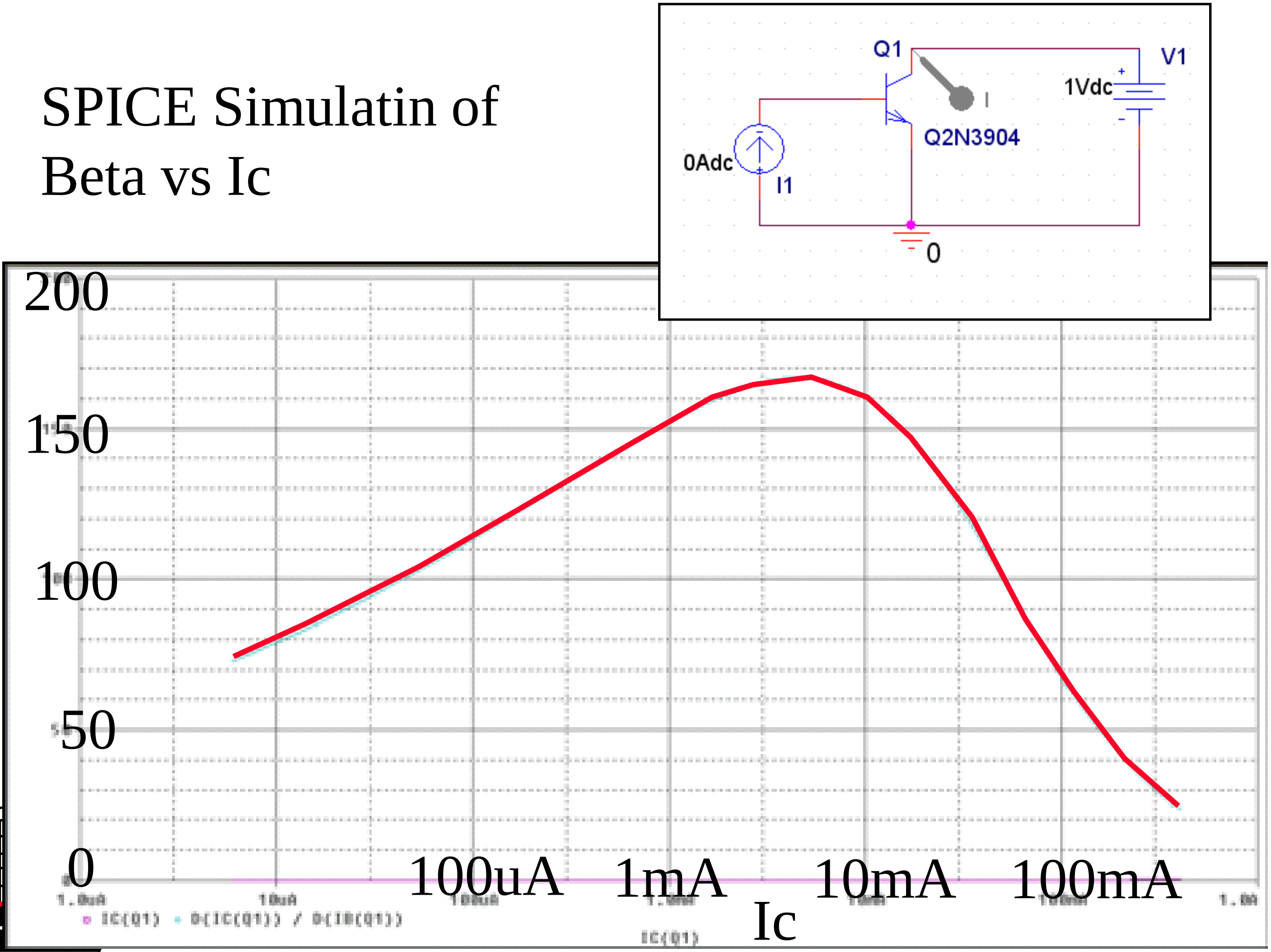


- - -●- - - Measured

▬ SPICE SIMULATED

SPICE SIMULATED

SPICE Simulatin of
Beta vs Ic

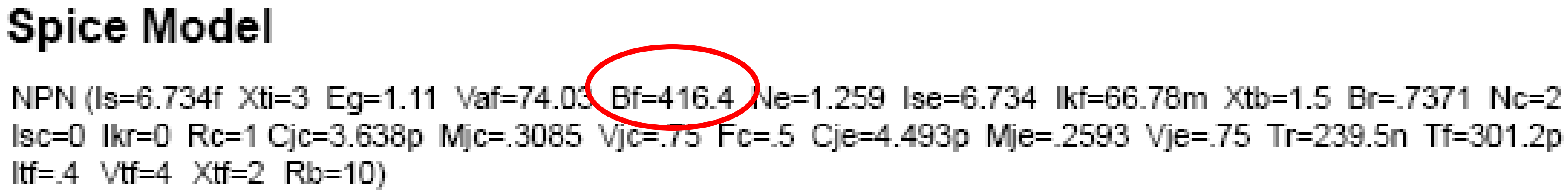


SPICE Model

```
        Q2N3904
        NPN
  IS      6.734000E-15
  BF    416.4
  NF      1
 VAF     74.03
 IKF       .06678
 ISE      6.734000E-15
  NE      1.259
  BR       .7371
  NR      1
  RB     10
  RC      1
 CJE      4.493000E-12
 MJE       .2593
 CJC      3.638000E-12
 MJC       .3085
  TF    301.200000E-12
 XTF      2
 VTF      4
 ITF       .4
  TR    239.500000E-09
 XTB      1.5
  CN      2.42
   D       .87
```

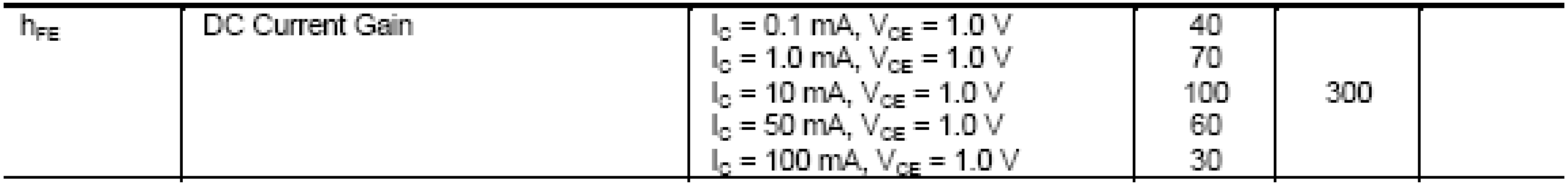
2N3904 SPICE MODEL

From the datasheet above



Spice Model

NPN (Is=6.734f Xti=3 Eg=1.11 Vaf=74.03 Bf=416.4 Ne=1.259 Ise=6.734 Ikf=66.78m Xtb=1.5 Br=.7371 Nc=2 Isc=0 Ikr=0 Rc=1 Cjc=3.638p Mjc=.3085 Vjc=.75 Fc=.5 Cje=4.493p Mje=.2593 Vje=.75 Tr=239.5n Tf=301.2p Itf=.4 Vtf=4 Xtf=2 Rb=10)



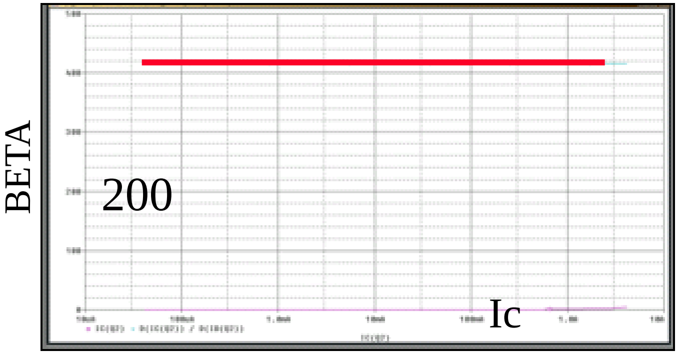
h_{FE}	DC Current Gain	I_C = 0.1 mA, V_{CE} = 1.0 V I_C = 1.0 mA, V_{CE} = 1.0 V I_C = 10 mA, V_{CE} = 1.0 V I_C = 50 mA, V_{CE} = 1.0 V I_C = 100 mA, V_{CE} = 1.0 V	40 70 100 60 30	300	

Why does the SPICE model have Bf of 416 when the maximum Bf=300

Answer: It is a model parameter and when combined with other model parameters give correct results. See next page.

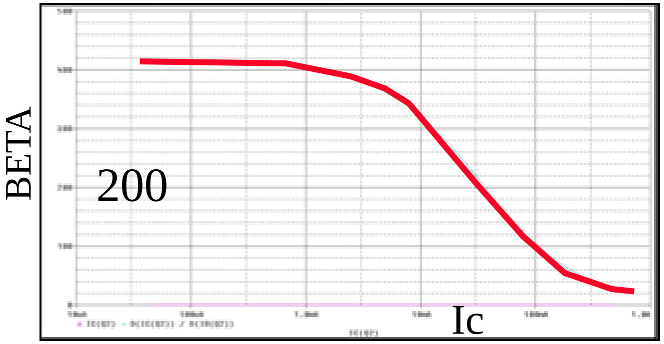
BJT SPICE PARAMETERS EFFECT ON BETA

When BF=419 is used by itself it gives incorrect results



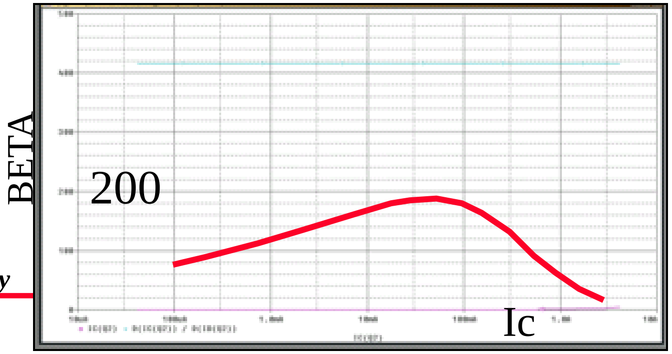
QRITNPN
NPN
BF 416

Adding IKF to the model helps reduce BF at high IC



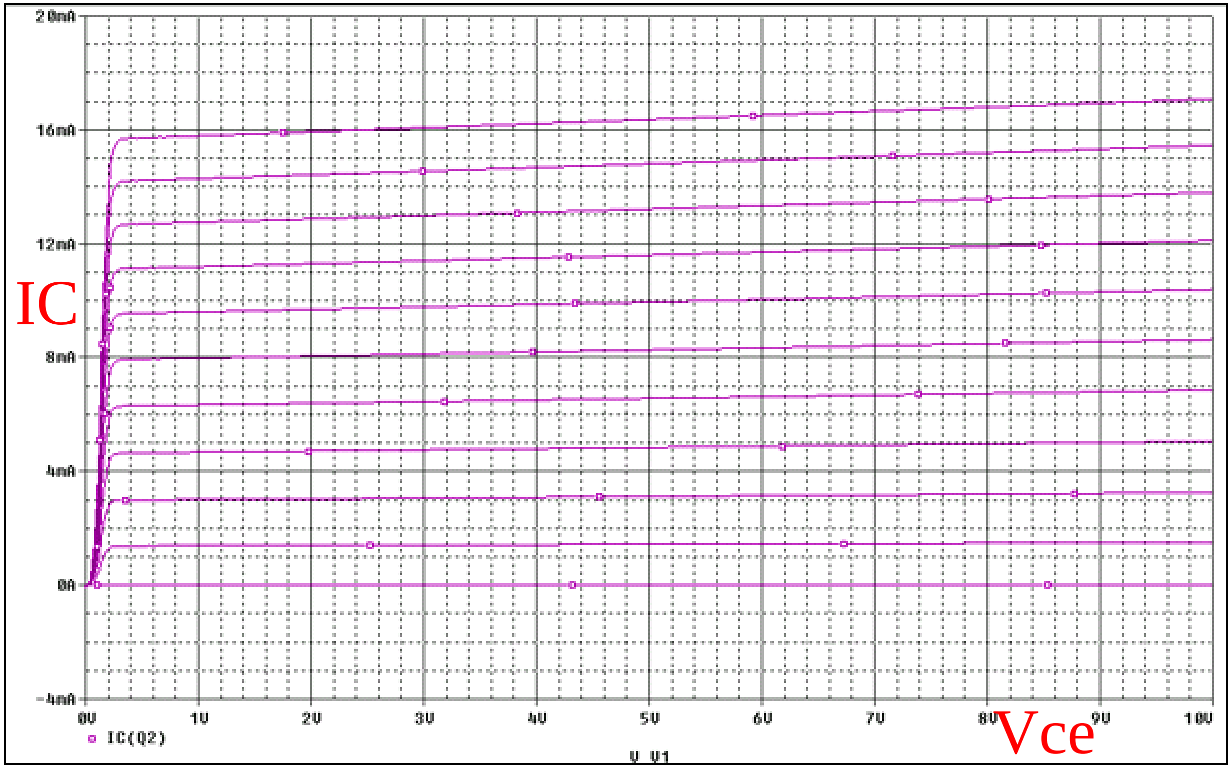
QRITNPN
NPN
BF 416
IKF .06678

Adding IS, ISE and NE makes the model give correct results for all IC



QRITNPN
NPN
BF 416
IKF .06678
IS 6.734000E-15
ISE 6.734000E-15
NE 1.259

IC=VCD FAMILY OF CURVES



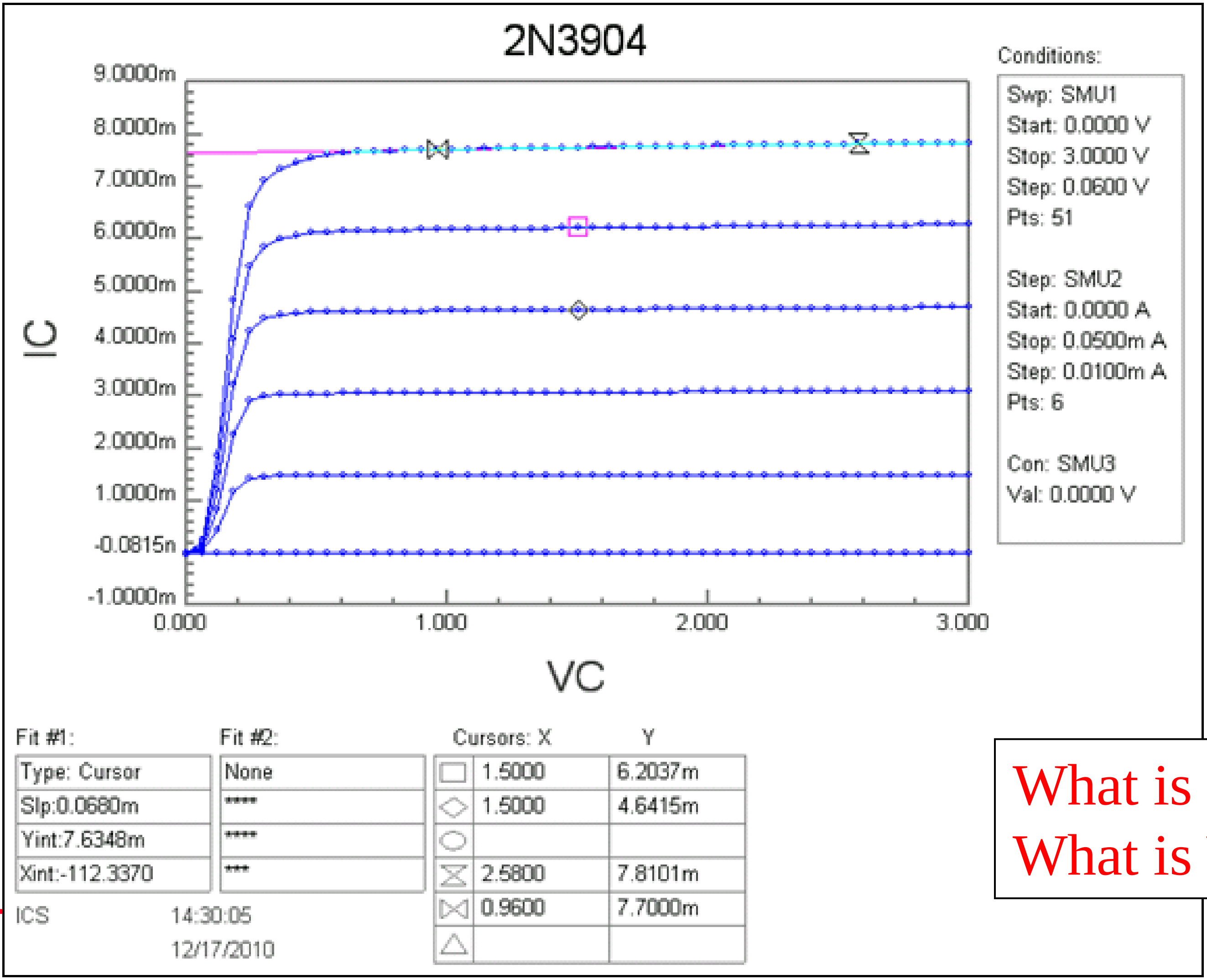
SPICE SIMULATION

SPICE MODEL

QRITNPN
NPN
IS 6.734000E-15
BF 416
IKF .06678
ISE 6.734000E-15
NE 1.259
RB 10
RC 1
VA 109

Rochester Institute of Technology
Microelectronic Engineering

2N3904 FORWARD ACTIVE



Conditions:

Swp: SMU1
Start: 0.0000 V
Stop: 3.0000 V
Step: 0.0600 V
Pts: 51

Step: SMU2
Start: 0.0000 A
Stop: 0.0500m A
Step: 0.0100m A
Pts: 6

Con: SMU3
Val: 0.0000 V

Fit #1:	Fit #2:
Type: Cursor	None
Slp:0.0680m	****
Yint:7.6348m	****
Xint:-112.3370	***

	Cursors: X	Y
□	1.5000	6.2037m
◇	1.5000	4.6415m
○		
⧖	2.5800	7.8101m
⋈	0.9600	7.7000m
△		

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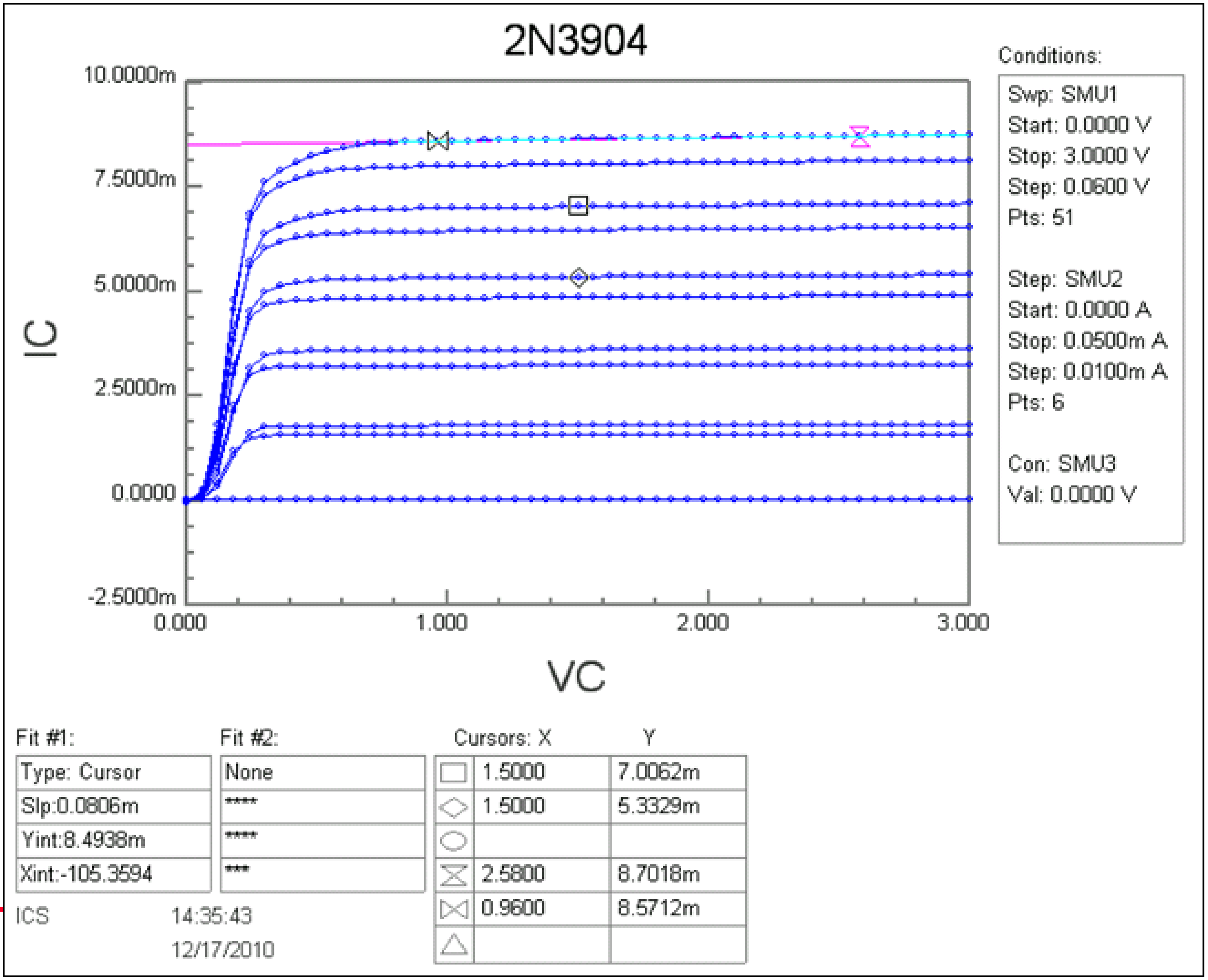
12/17/2010

What is Beta?
What is VA?

TEMPERATURE EFFECT ON FAMILY OF CURVES



Conditions:

Swp: SMU1
Start: 0.0000 V
Stop: 3.0000 V
Step: 0.0600 V
Pts: 51

Step: SMU2
Start: 0.0000 A
Stop: 0.0500m A
Step: 0.0100m A
Pts: 6

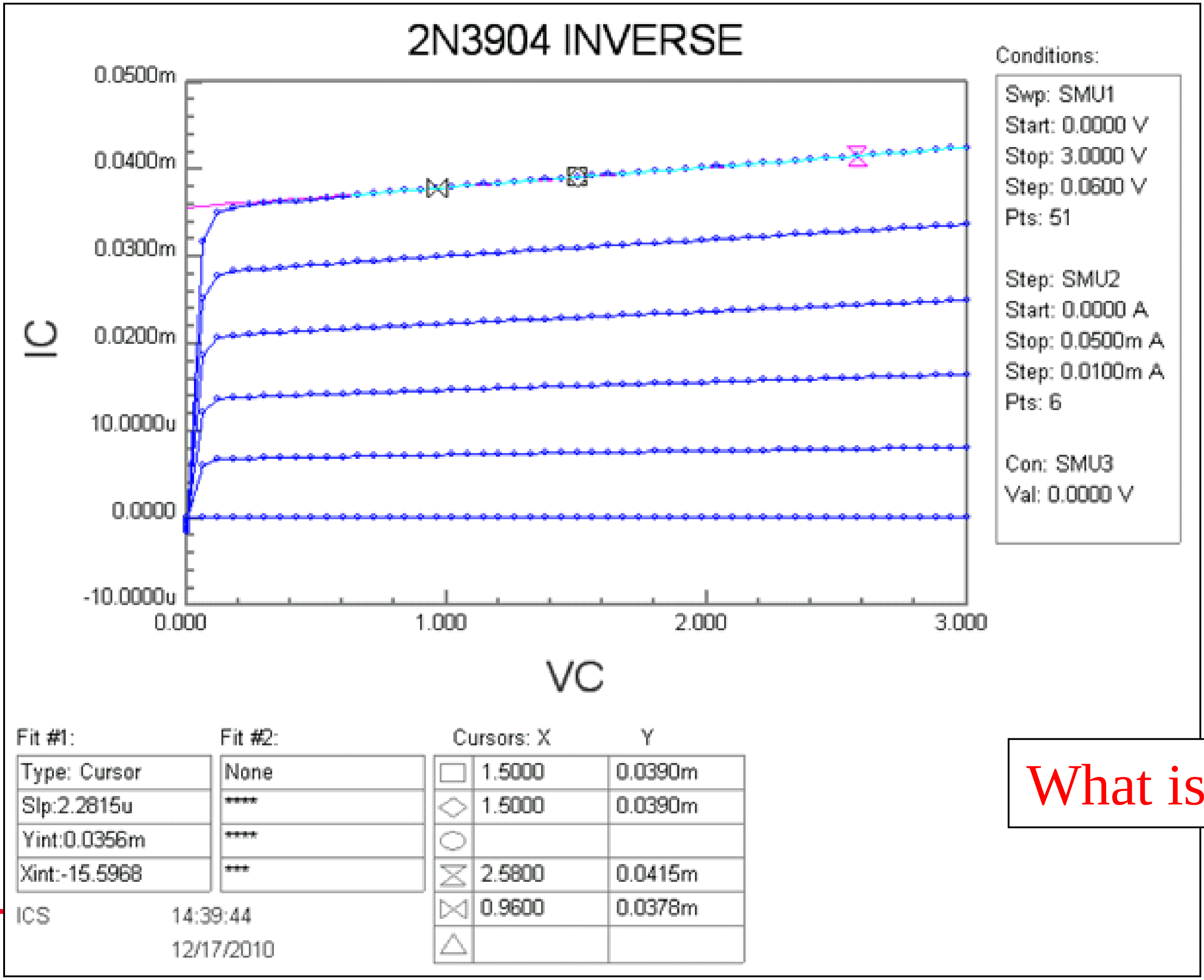
Con: SMU3
Val: 0.0000 V

Fit #1:	Fit #2:
Type: Cursor	None
Slp:0.0806m	****
Yint:8.4938m	****
Xint:-105.3594	***

	Cursors: X	Y
□	1.5000	7.0062m
◇	1.5000	5.3329m
○		
⧖	2.5800	8.7018m
⋈	0.9600	8.5712m
△		

ICS 14:35:43
12/17/2010

2N3904 INVERSE MODE



Conditions:

Swp: SMU1
Start: 0.0000 V
Stop: 3.0000 V
Step: 0.0600 V
Pts: 51

Step: SMU2
Start: 0.0000 A
Stop: 0.0500m A
Step: 0.0100m A
Pts: 6

Con: SMU3
Val: 0.0000 V

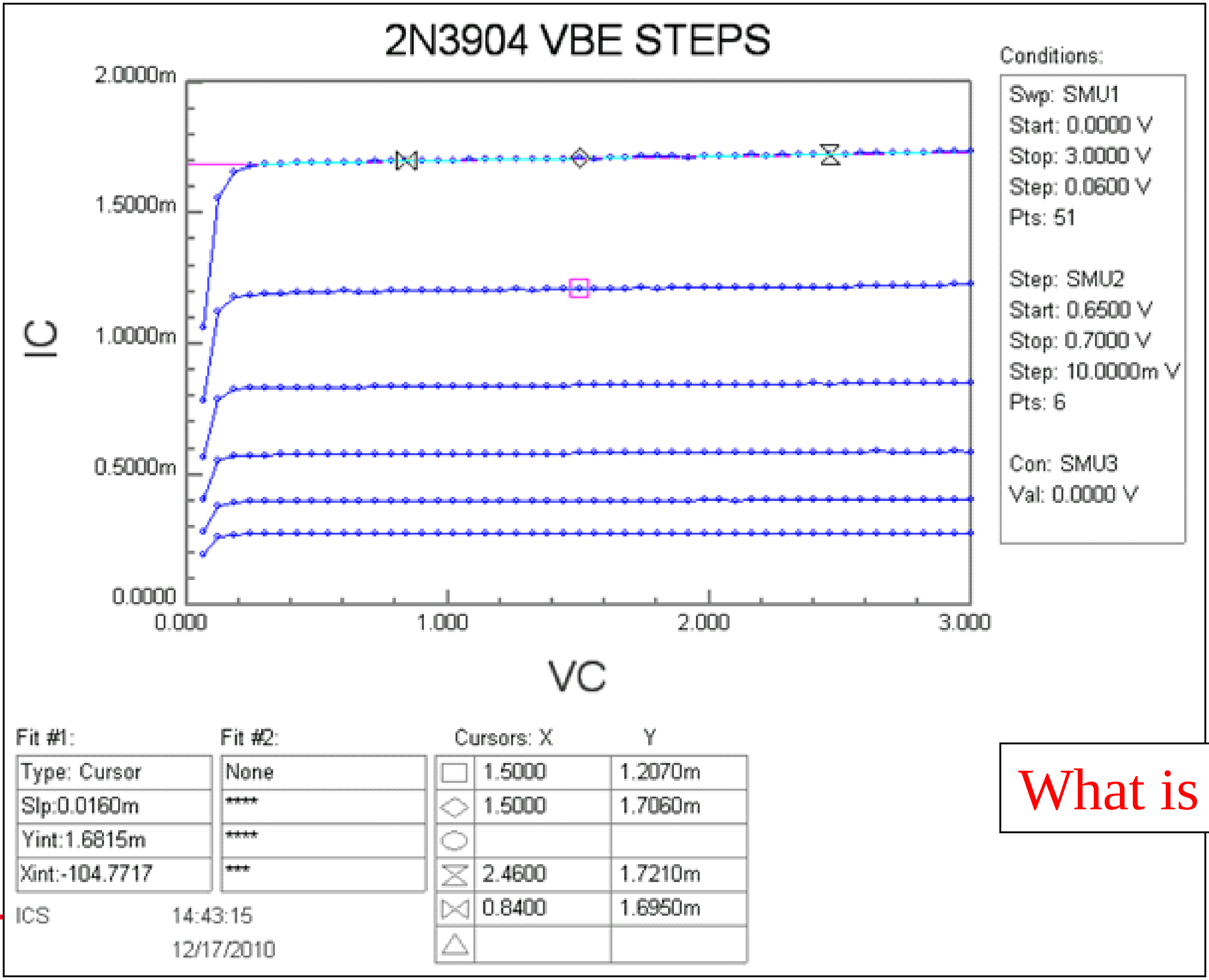
Fit #1:	Fit #2:
Type: Cursor	None
Slp:2.2815u	*****
Yint:0.0356m	*****
Xint:-15.5968	****

Cursors:	X	Y
□	1.5000	0.0390m
◇	1.5000	0.0390m
○		
⧗	2.5800	0.0415m
⋈	0.9600	0.0378m
△		

ICS 14:39:44
12/17/2010

What is Beta?

2N3904 VBE STEPS



2N3904 VBE STEPS

Conditions:

Swp: SMU1
Start: 0.0000 V
Stop: 3.0000 V
Step: 0.0600 V
Pts: 51

Step: SMU2
Start: 0.6500 V
Stop: 0.7000 V
Step: 10.0000m V
Pts: 6

Con: SMU3
Val: 0.0000 V

Fit #1:	Fit #2:
Type: Cursor	None
Slp:0.0160m	*****
Yint:1.6815m	*****
Xint:-104.7717	***

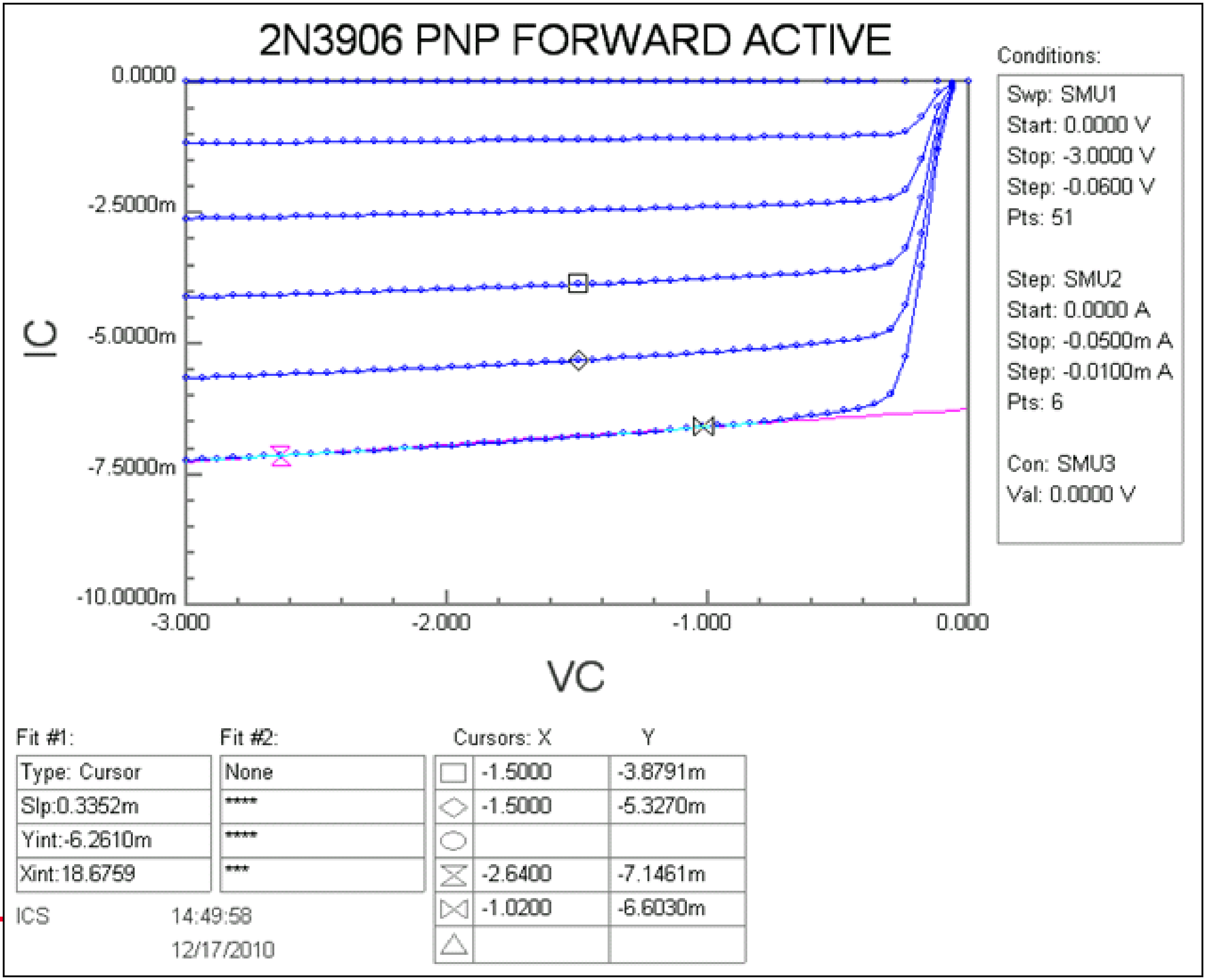
Cursors:	X	Y
☐	1.5000	1.2070m
◇	1.5000	1.7060m
○		
⧖	2.4600	1.7210m
⋈	0.8400	1.6950m
△		

ICS

14:43:15
12/17/2010

What is gm?

PNP FORWARD ACTIVE



Conditions:

Swp: SMU1
Start: 0.0000 V
Stop: -3.0000 V
Step: -0.0600 V
Pts: 51

Step: SMU2
Start: 0.0000 A
Stop: -0.0500m A
Step: -0.0100m A
Pts: 6

Con: SMU3
Val: 0.0000 V

Fit #1:	Fit #2:
Type: Cursor	None
Slp:0.3352m	****
Yint:-6.2610m	****
Xint:18.6759	***

ICS 14:49:58
12/17/2010

Cursors:	X	Y
□	-1.5000	-3.8791m
◇	-1.5000	-5.3270m
○		
⧖	-2.6400	-7.1461m
⋈	-1.0200	-6.6030m
△		

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3. UTMOST III Modeling Manual-Vol.1. Ch. 5. From Silvaco International.
4. ATHENA USERS Manual, From Silvaco International.
5. ATLAS USERS Manual, From Silvaco International.
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7. ICCAP Manual, Hewlet Packard
8. PSpice Users Guide.

LAB WORK USING HP4145

Obtain I-V plot for BE junction
Obtain I-V plot for BC junction
Obtain I-V plot for C-E
Obtain Ic-Vce family of curves for 2n3904 (for different Ib’s)
Extract VA Early Voltage
Extract Beta at 5 different IC values (0.1mA to 100mA)
Obtain Ic-Vce family of curves at elevated temperature
Obtain Ic-Vce family of curves for inverse operation
Extract Beta Inverse
Obtain Ic-Vce curves for different Vbe

Repeat some or all of above for 2N3906

HOMEWORK – BJT CHARACTERIZATION

Use SPICE to obtain the following:

1. Ic-Vce family of curves for 2N3904
2. Extract VA Early Voltage
3. Extract Beta at 5 different IC values (0.1mA to 100mA)
4. Obtain Ic-Vce family of curves at elevated temperature
5. Obtain Ic-Vce family of curves for inverse operation
6. Extract Beta Inverse
7. Obtain Ic-Vce curves for different Vbe