3EJ4 Lab1

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Part1:

For the NPN-BJT 2N3904 characterized, if we want to bias this device to conduct a collector current IC ≈ 1.0 mA at the lowest VCE value, answer the following questions.

Q1. (7 Points) Based on the simulated data in Steps 1.2-1.4, use the bias condition giving the closest IC value to the desired collector current, find out

V+ (VCC)	V- (VE)	V(Q1C) (Volt)	V(Q1B) (Volt)	VCE (Volt)	VBEon (Volt)	RC (ohm)	RB (ohm)	IC (A)	IB (A)	β = IC/IB	|VA| (V)	ro=VA/IC	gm = IC/25mV	rπ = 25mV/IB
0.5	-1.5	3.98E-01	-8.79E-01	1.898	0.621	100	1.00E+05	0.00102	8.79E-06	117		9.76E+05	4.10E-02	2845

(1) What are the simulated VBEon in volt and the base current IB in μA?

Ans: VBEon = 0.621V, IB = 8.79μA

(2) What is the β = IC/IB value at this IC?

Ans: 117

(3) What is the early voltage |VA| in volt?

Ans: 1000V

(4) What is the output resistance ro in kΩ?

Ans: 976 kΩ

(5) What is the transconductance gm in mS?

Ans: 41mS

(6) What is the input resistance rπ in kΩ?

Ans: 2.845 kΩ

Q2. (8 Points) Based on the measured data in Step 1.8, use the same bias condition used in Q1 (or the first reliable data if that bias condition is an outlier), find out

V+ (VCC)	V- (VE)	Channel 1 (VC)	Channel 2 (VB)	VCE (Volt)	VBEon (Volt)	RC (ohm)	RB (ohm)	IC (A)	IB (A)	β = IC/IB	|VA| (V)	ro=VA/IC	gm = IC/25mV	rπ = 25mV/IB
0.5	-1.5	3.20E-01	-8.17E-01	1.82	0.6826	100	1.00E+05	0.0018	8.17E-06	220		1.00E+05	7.20E-02	3058

(1) How much is the measured collector current IC in mA?

Ans: 1.8mA

(2) What are the measured VBEon in volt and the base current IB in μA?

Ans: VBEon = 0.6826V, IB = 8.17μA

(3) What is the β = IC/IB value at this IC?

Ans: 220

(4) What is the early voltage |VA| in volt?

Ans: 180V

(5) What is the output resistance ro in kΩ?

Ans: 100kΩ

(6) What is the transconductance gm in mS?

Ans: 72mS

(7) What is the input resistance rπ in kΩ?

Ans: 3.058kΩ

Part2:

For the PNP-BJT 2N3906 characterized, if we want to bias this device to conduct a collector current IC≈1.0 mA at the lowest VEC value, answer the following questions.

Q3. (7 Points) Based on the simulated data in Steps 2.2-2.4, use the bias condition giving the closest IC value to the desired collector current, find out

V+ (VE)	V- (VCC)	V(Q1C) (Volt)	V(Q1B) (Volt)	VEC (Volt)	VEBon (Volt)	RC (ohm)	RB (ohm)	IC (A)	IB (A)	β = IC/IB	|VA| (V)	ro=VA/IC	gm = IC/25mV	rπ = 25mV/IB
1.5	-0.5	-3.97E-01	8.40E-01	1.90	0.660	100	1.00E+05	1.03E-03	8.40E-06	123		1.39E+05	4.12E-02	2976

(1) What are the simulated VEBon in volt and the base current IB in μA?

Ans: VEBon = 0.660V, IB = 8.40μA

(2) What is the β = IC/IB value at this IC?

Ans: 123

(3) What is the early voltage |VA| in volt?

Ans: 133

(4) What is the output resistance ro in kΩ?

Ans: 139kΩ

(5) What is the transconductance gm in mS?

Ans: 41.2mS

(6) What is the input resistance rπ in kΩ?

Ans: 2.976kΩ

Q4. (8 Points) Based on the measured data in Step 2.8, use the same bias condition used in Q3 (or the first reliable data if that bias condition is an outlier), find out

V+ (VE)	V- (VCC)	Channel 1 (VC)	Channel 2 (VB)	VEC (Volt)	VEBon (Volt)	RC (ohm)	RB (ohm)	IC (A)	IB (A)	β = IC/IB	|VA| (V)	ro=VA/IC	gm = IC/25mV	rπ = 25mV/IB
1	-0.5	-4.01E-01	3.54E-01	1.40	0.646	100	1.00E+05	9.90E-04	3.54E-06	280		3.36E+04	3.96E-02	7066

(1) How much is the measured collector current IC in mA?

Ans: 0.990mA

(2) What are the measured VEBon in volt and the base current IB in μA?

Ans: VEBon = 0.646V, IB = 3.54μA

(3) What is the β = IC/IB value at this IC?

Ans: 280

(4) What is the early voltage |VA| in volt?

Ans: 33V

(5) What is the output resistance ro in kΩ?

Ans: 33.6kΩ

(6) What is the transconductance gm in mS?

Ans: 39.6mS

(7) What is the input resistance rπ in kΩ?

Ans: 7.066kΩ

Part3:

Q5. (10 Points) Express the base current IB as a function of VBB, RBB, VBEon, R3, VEE, and β

Ans: $I_B = \frac{V_{BB}-(V_{EE}+V_{BEon})}{R_{BB}+(\beta+1)R3} = \frac{R_2}{R_1+R_2}\frac{-(V_{EE}+\Delta V_{EE})}{R_{BB}+(\beta+1)R3} - \frac{V_{BEon}}{R_{BB}+(\beta+1)R3}$

Solution:

Q5: Apply loop analysis from X3 to X1 From Figure 7

$$V_{BB} - R_{BB} I_B - V_{BEon} - I_E R_3 - V_{EE} = 0 \quad .$$

$I_E = (\beta+1) \cdot I_B$

$$V_{BB} - V_{BEON} - V_{EE} = I_B \left(R_{BB} + R_3 \cdot (\beta+1)\right)$$

$$I_B = \frac{V_{BB} - V_{BEON} - V_{EE}}{R_{BB} + R_3 \cdot (\beta+1)}$$

(1) $V_{BB} = \frac{R_1}{R_1+R_2} V_{EE}$

(2) $R_{BB} = R_1 \| R_2 = \frac{R_1 R_2}{R_1+R_2}$

(3) $I_B = \frac{V_{BB} - (V_{EE} + V_{BEON})}{R_{BB}}$

$$I_B = \frac{V_{BB} - V_{BEON} - V_{EE}}{R_{BB} + R_3 \cdot (\beta+1)} = \frac{\frac{R_1}{R_1+R_2} V_{EE} - V_{EE} - V_{BEON}}{R_{BB} + R_3(\beta+1)}$$

$$\frac{R_1 + R_2}{R_1+R_2} = \frac{-R_2}{R_1+R_2}$$

$$= \frac{V_{EE}\left(\frac{R_1}{R_1+R_2} - 1\right) - V_{BEON}}{R_{BB} + R_3(\beta+1)}$$

$$= \frac{-\frac{R_2}{R_1+R_2} V_{EE} - V_{BEON}}{R_{BB} + R_3(\beta+1)}$$

$$= \frac{R_2}{R_1+R_2} \cdot \frac{(-V_{EE})}{R_{BB}+R_3(\beta+1)} - \frac{V_{BEON}}{R_{BB}+R_3(\beta+1)}$$

$$\therefore \; I_B = \frac{V_{BB} - V_{BEON} - V_{EE}}{R_{BB} + R_3 \cdot (\beta+1)} = \frac{R_2}{R_1+R_2} \frac{(-V_{EE})}{R_{BB}+R_3(\beta+1)} - \frac{V_{BEON}}{R_{BB}+R_3(\beta+1)}$$

Q6. (10 Points) Comparing the IB expression obtained in Q5 with (3), what is the difference between these two equations? For a change ΔVEE in the power supply VEE, derive equations for the resulted change in the base current ΔIB using (3) and the IB expression obtained in Q5. Show that the emitter resistor R3 reduces the change in the base current ΔIB as a result of the change ΔVEE in the power supply VEE

Ans:

The difference between these two equations is there is a following Resistance equation $(\beta + 1)R3$ in Q5 if we don't assume R3 is zero from the **Fig.7**.

Equations for the resulted change in the base current ΔIB.

Using expression (3): $$\Delta \mathrm{IB} = \frac{R_2}{R_1+R_2}\frac{-\Delta V_{EE}}{R_{BB}}$$

Using expression (Q5): $$\Delta \mathrm{IB} = \frac{R_2}{R_1+R_2}\frac{-\Delta V_{EE}}{R_{BB}+(\beta+1)R3}$$

As seen from the two expressions, if there is a change ΔVEE in the power supply, all other resistors stay constant, the emitter resistor R3(Resistor must be positive) will increase the denominator values in order to reduce the overall change of current ΔIB.

Solution:

Q6:

(5) $$I_B = \frac{V_{BB} - V_{BEON} - V_{EE}}{R_{BB} + R_3 \cdot (\beta+1)} = \frac{R_2}{R_1+R_2}\frac{(-V_{EE})}{R_{BB}+R_3(\beta+1)} - \frac{V_{BEON}}{R_{BB}+R_3(\beta+1)}$$

(3) $$I_B = \frac{V_{BB} - (V_{EE} + V_{BEON})}{R_{BB}} = \frac{R_2}{R_1+R_2}\frac{(-V_{EE})}{R_{BB}} - \frac{V_{BEON}}{R_{BB}}$$

Using expression (3), if a change ΔV_{EE}, $V_{EE} + \Delta V_{EE}$

$$\therefore I_{B\,final} = \frac{R_2}{R_1+R_2}\frac{-(V_{EE}+\Delta V_{EE})}{R_{BB}} - \frac{V_{BEON}}{R_{BB}}$$

$$\Delta I_B = I_{B\,final} - I_B = \frac{R_2}{R_1+R_2}\frac{-(V_{EE}+\Delta V_{EE})}{R_{BB}} - \frac{V_{BEON}}{R_{BB}} - \frac{R_2}{R_1+R_2}\frac{(-V_{EE})}{R_{BB}} - \frac{V_{BEON}}{R_{BB}}$$

$$= \frac{R_2}{R_1+R_2}\left(\frac{\cancel{-V_{EE}} - \Delta V_{EE} + \cancel{V_{BEON}} + \cancel{V_{EE}} - \cancel{V_{BEON}}}{R_{BB}}\right)$$

$$= \frac{R_2}{R_1+R_2}\frac{(-\Delta V_{EE})}{R_{BB}}$$

Using expression (5), if a change ΔEE. $V_{EE} + \Delta V_{EE}$

$$\therefore I_{B\,final} = \frac{R_2}{R_1+R_2}\frac{-(V_{EE}+\Delta V_{EE})}{R_{BB}+R_3(\beta+1)} - \frac{V_{BEON}}{R_{BB}+R_3(\beta+1)}$$

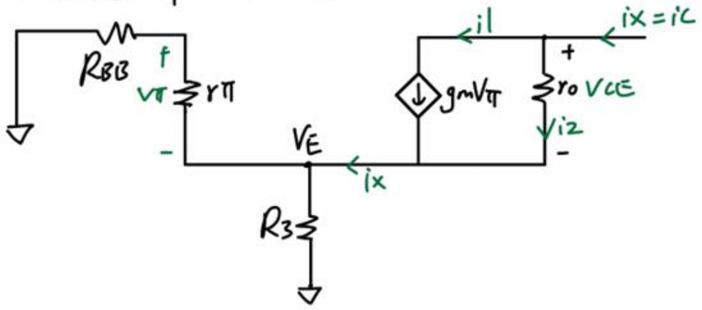
$$\Delta I_B = I_{B\,final} - I_B = \frac{R_2}{R_1+R_2}\cdot\frac{-(V_{EE}+\Delta V_{EE})}{R_{BB}+R_3(\beta+1)} - \frac{V_{BEON}}{R_{BB}+R_3(\beta+1)}$$
$$- \frac{R_2}{R_1+R_2}\cdot\frac{(-V_{EE})}{R_{BB}+R_3(\beta+1)} - \frac{V_{BEON}}{R_{BB}+R_3(\beta+1)}$$
$$= \frac{R_2}{R_1+R_2}\left(\frac{\cancel{-V_{EE}} - \Delta V_{EE} + \cancel{V_{BEON}} + \cancel{V_{EE}} - \cancel{V_{BEON}}}{R_{BB}+R_3(\beta+1)}\right) = \frac{R_2}{R_1+R_2}\,\frac{(-\Delta V_{EE})}{R_{BB}+R_3(\beta+1)}$$

$R_3\uparrow$, $\Delta I_B\downarrow$, $R_3 \rightarrow$ resistor must be positive

Q7. (15 Points) Inserting the feedback R3 at the emitter of the BJT not only stabilizes the IB but also improves (or increases) the output resistance Ro of the current sink shown in Fig. 6/Fig. 7 (i.e., *I*o is more stable when there is a change in VCE). Using a π-model for the BJT, prove that the output resistance of the current sink is $R_o = r_o + [R_3||(R_{BB}+r_\pi)]\left[1 + g_m r_o\left(\frac{r_\pi}{R_{BB}+r_\pi}\right)\right]$.

Ans:

Q7. π-model of the BJT



$$R_o = \frac{V_x}{i_x}$$

$i_1 = g_m V_\pi$, $\quad i_2 = i_x - i_1 = i_x - g_m V_\pi$, $\quad V_{CE} = r_o \cdot i_2 = r_o\cdot(i_x - g_m V_\pi)$

$V_E = i_x\cdot(R_{BB}+r_\pi)\,||\,R_3$

$$V_\pi = -V_E\cdot\frac{r_\pi}{R_{BB}+r_\pi}$$

$V_x = V_{CE} + V_E$,

$$= r_o\cdot\left(i_x - g_m\cdot\left(-V_E\cdot\frac{r_\pi}{R_{BB}+r_\pi}\right)\right) + i_x\cdot(R_{BB}+r_\pi)\,||\,R_3$$

$$= r_o\cdot\cancel{i_x} + r_o\cdot g_m\cdot\cancel{i_x}\cdot(R_{BB}+r_\pi)\,||\,R_3\cdot\frac{r_\pi}{R_{BB}+r_\pi} + \cancel{i_x}\cdot(R_{BB}+r_\pi)\,||\,R_3$$

$$= i_x\left(r_o + r_o g_m \underline{(R_{BB}+r_\pi)\,||\,R_3}\cdot\frac{r_\pi}{R_{BB}+r_\pi} + \underline{(R_{BB}+r_\pi)\,||\,R_3}\right)$$

$$= \cancel{i_x}\left(r_o + (R_{BB}+r_\pi)\,||\,R_3)\left(g_m r_o\cdot\frac{r_\pi}{R_{BB}+r_\pi} + 1\right)\right)$$

$$\therefore R_o = \frac{V_x}{i_x} = r_o + [R_3 \| (R_{BB} + r_\pi)]\left[1 + g_m r_o \left(\frac{r_\pi}{R_{BB} + r_\pi}\right)\right]$$

Q8. (10 Points) Inserting the feedback R_3 at the emitter of the BJT improves the stabilization of the Q-point at the cost of increased $V_{o,min}$. What is the $V_{o,min}$ of the constant current sink when R3≠0?

Ans:

Given $V_{o,min}$ formula is $V_{o,min} = V_{EE} + 0.3V$, this is the mimum voltage if we assume when R3 is zero. After inserting the feedback R3, the current will flow through the R3 and generated a new voltage drop across R3, this voltage can be calculated as VR3 = IR3 * R3 by applying the Ohm's law. Since IR3 is the current flow through the emitter, there IR3 = IE and VR3 = IE * R3.

As a result, after inserting the feedback R3, the $V_{o,min} = V_{EE} + 0.3V + VR3 = V_{EE} + 0.3V + IE * R3.$

Q9. (15 Points) For V_{EE} = -5V, if we want to design a current sink with I_o = 1.0 mA and $V_{o,min}$=-1V using the NPN-BJT 2N3094 characterized in Q1, what is the resistance value for R3? To reduce the DC power consumption of R1 and R2, we usually choose large resistance values (in tens or hundreds of kΩ) for R1 and R2. Suppose we choose R_2 = 100 kΩ, calculate R1 in kΩ. Verify the Io vs. VCC characteristics of the design by sweeping VCC from -5V to 5V with a 0.05V step and post the screenshot of the simulated Io vs. VCC characteristics.

Ans:

R3=3.67 kΩ, R1=13.09 kΩ

Io vs. VCC characteristics:

Solution:

Q9. Given $V_{EE} = -5V,\ I_o = 1.0mA,\ V_{o,min} = -1V,\ \beta = 117$

(Q8) $V_{o,min} = V_{EE} + 0.3V + I_E \cdot R_3$

$I_o = I_C = 1.0mA,\ I_C = \beta \cdot I_B$

$1.0 = 117 \cdot I_B$

$I_B = \frac{1}{117} mA$

$I_E = (\beta + 1) I_B$

$= 118 \cdot \frac{1}{117} = \frac{118}{117} mA$

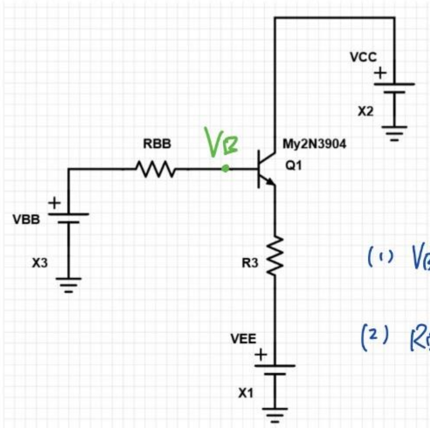
$-4.7V$

$-1V = -5V + 0.3V + \frac{118}{117} mA \cdot R_3$

$3.7V = \frac{118}{117} mA \cdot R_3$

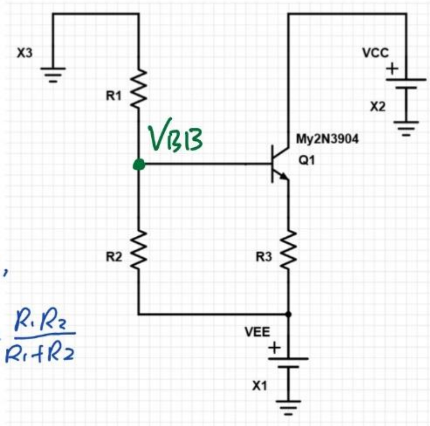
$R_3 = 3.7 \times \frac{117}{118} = 3.67 k\Omega$

$R_2 = 100k\Omega$



(1) $V_{BB} = \frac{R_1}{R_1+R_2} V_{EE}$,

(2) $R_{BB} = R_1 \parallel R_2 = \frac{R_1 R_2}{R_1+R_2}$



$V_{BB} = V_B + I_B \cdot R_{BB}$

$V_{BB} = \frac{R_1}{R_1+R_2} V_{EE}$

$\therefore \quad I_B \cdot R_{BB} + V_B = \frac{R_1}{R_1+R_2} V_{EE}$

$I_B \cdot \frac{R_1 R_2}{R_1+R_2} + V_B = \frac{R_1}{R_1+R_2} V_{EE}$

$\frac{1}{117} \cdot \frac{100 R_1}{100+R_1} - 0.67763 = \frac{R_1}{100+R_1} \times -5$

$R_1 = 13.089 \doteq 13.09 \, k\Omega$

$I_B = \frac{1}{117} mA$, $I_E = \frac{118}{117} mA$

$R_2 = 100 k\Omega$

$V_{EE} = -5$

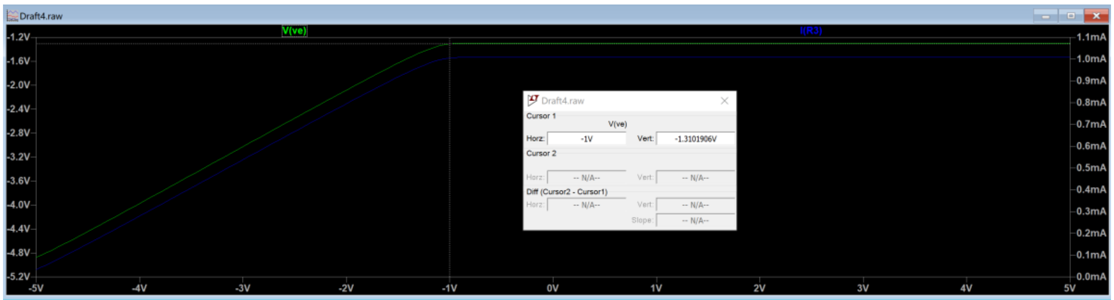
$V_{EE} + I_E R_3 + V_{BEON} = V_B$

$-5 + \frac{118}{117} \times 3.67 + 0.621 = V_B$

$V_B = -0.67763$

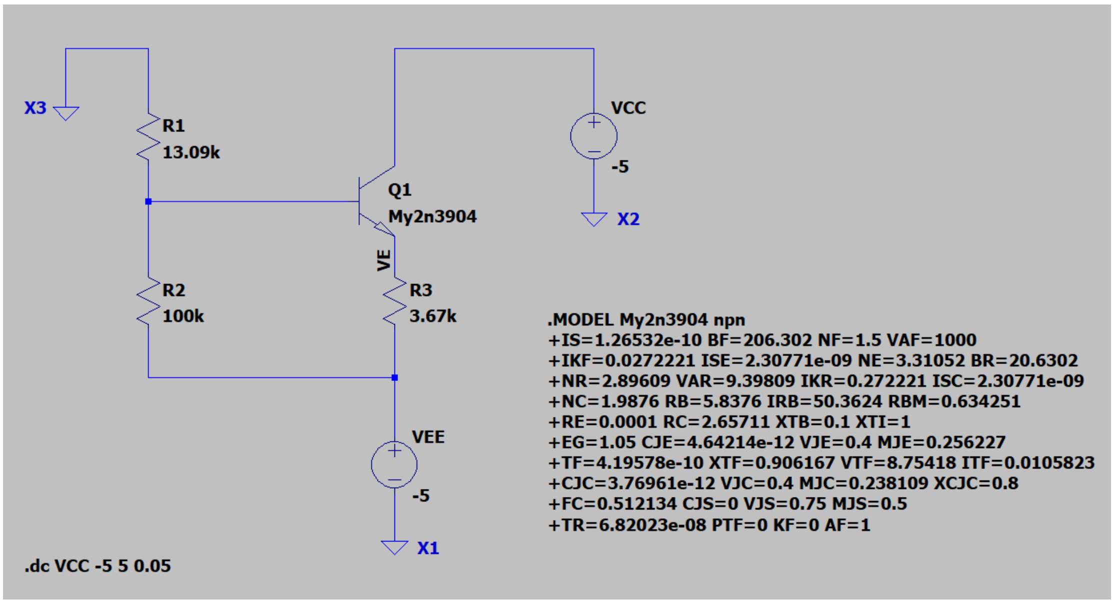
Q10. (10 Points) When designing the constant current sink shown in Fig. 6, we assume that $|V_{CE}| \geq 0.3V$ and Q_1 works in the active region. Based on the resistance values obtained in Q9, sweep V_{CC} in Fig. 6 from -5 V to +5V with a 0.05 V step and measure V_E and I_C to determine the $|V_{CE}|$ required for Q1 to work in the active region.

Ans:



As observed from the simulation graph, the horizontal axis is the V_{CC} DC sweep voltage, and the vertical axis is the V_E voltage. The active region is described as the horizontal line on the graph. The breakpoint observed of V_E and V_{CC} is -1.3101906V and -1V separately. Therefore, the VCE can be calculated as VCE = VCC – VE = -1V + 1.3101906V = 0.3101906≈0.31V which meets the assumption.

Circuit schematic for the Q9 and Q10:


X3
R1
13.09k
Q1
My2n3904
VCC
-5
X2
VE
R2
100k
R3
3.67k
VEE
-5
X1
.MODEL My2n3904 npn
+IS=1.26532e-10 BF=206.302 NF=1.5 VAF=1000
+IKF=0.0272221 ISE=2.30771e-09 NE=3.31052 BR=20.6302
+NR=2.89609 VAR=9.39809 IKR=0.272221 ISC=2.30771e-09
+NC=1.9876 RB=5.8376 IRB=50.3624 RBM=0.634251
+RE=0.0001 RC=2.65711 XTB=0.1 XTI=1
+EG=1.05 CJE=4.64214e-12 VJE=0.4 MJE=0.256227
+TF=4.19578e-10 XTF=0.906167 VTF=8.75418 ITF=0.0105823
+CJC=3.76961e-12 VJC=0.4 MJC=0.238109 XCJC=0.8
+FC=0.512134 CJS=0 VJS=0.75 MJS=0.5
+TR=6.82023e-08 PTF=0 KF=0 AF=1
.dc VCC -5 5 0.05