Bipolar Junction Transistor

BJT

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Version 1.01

Bipolar Junction Transistor

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Presentation in Three Chapters

- Transistor History – The Road To Silicon - 15 min
- BJT Electrical Characteristics – 35 min
- Strange and Unusual BJT Circuits – 10 min

Ambitious time-plan – strict 60 minute allocation limit
Short questions OK – best confined to chapter 2
Additional 10 minute allocation for further questions at the presentation's end
Presentation on CD available for takeaway – multiple formats – extra information

Bipolar Junction Transistor

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- **Transistor History – The Road To Silicon – 15 minutes**

Who were responsible for the transistors of today?

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Transistor History – The Road To Silicon

John Bardeen, William Shockley and Walter Brattain at Bell Labs, 1948.

What did their first transistor look like?

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Transistor History – The Road To Silicon

- First Point Contact Germanium Transistor
- Replica of Original
- Invented by Shockley, Bardeen and Brattain
- Patented circa 1947
- But Ignored Shockley!
- Shockley was peeved

Note: The “Schottky diode” was not invented by Shockley but the “Shockley diode” was

Next – An **patent** excerpt from Bardeen and Brattain

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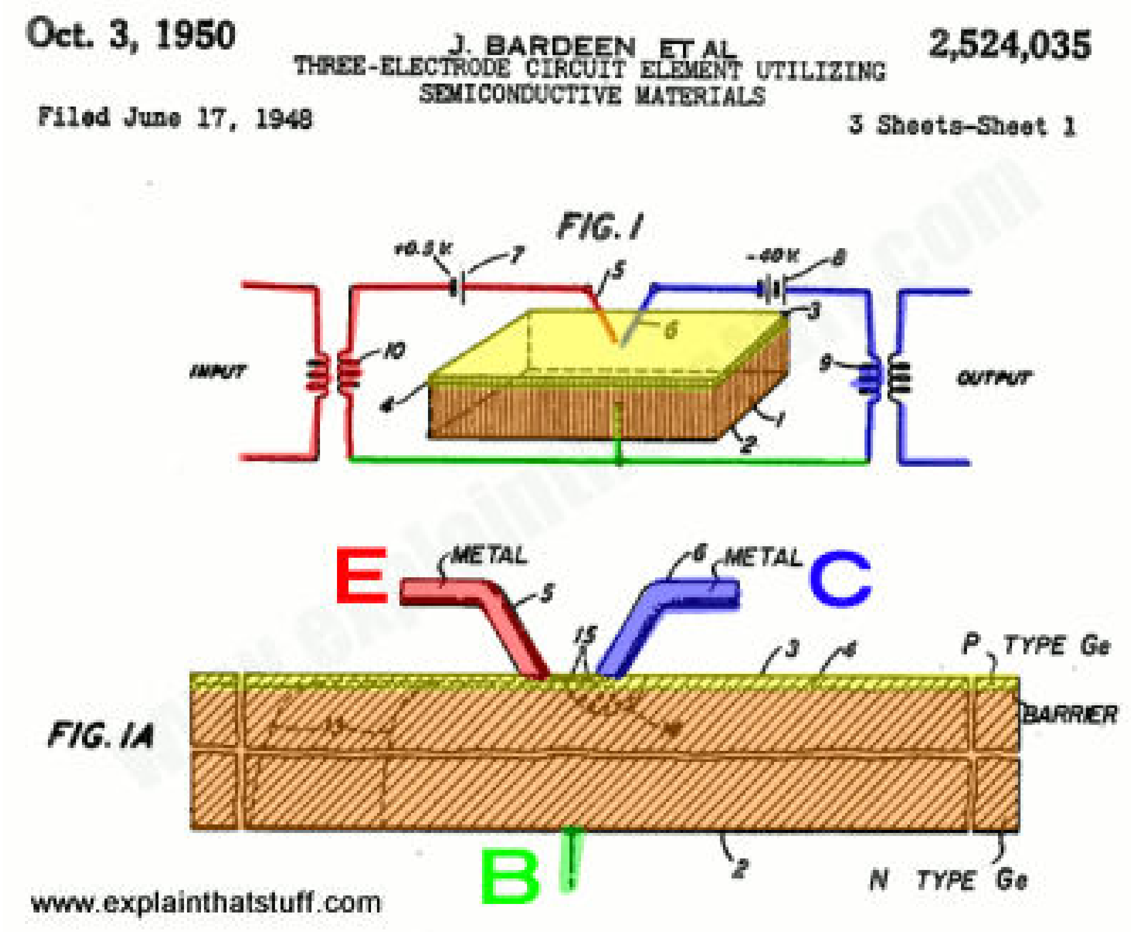
Transistor History – The Road To Silicon



Excerpt from Patent Filed by John Bardeen & Walter Brattain and October 3, 1950, ignoring their lab leader William Shockley

But how well did it work?

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Transistor History – The Road To Silicon

- Operated in “Common Base” Mode
- Current Amplification 2 ~ 3 times
- Voltage Amplification ~ 50 times
- Power Amplification 100 ~ 150 times
- Maximum Frequency ~ 1 MHz
- Very High Noise Floor, NF > 20 dB

- **Summary – *poor by modern standards***

Still, these were commercialized and enjoyed a short few years of use – by hobbyists!

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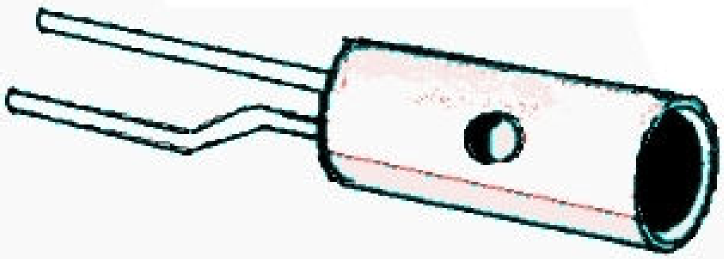
Transistor History – The Road To Silicon

First commercially available point-contact transistor



- Point Contact Transistor Introduced by Bell Labs
- Commercial Release in 1949
- Competing junction transistor - theory starts in 1948 by William Shockley

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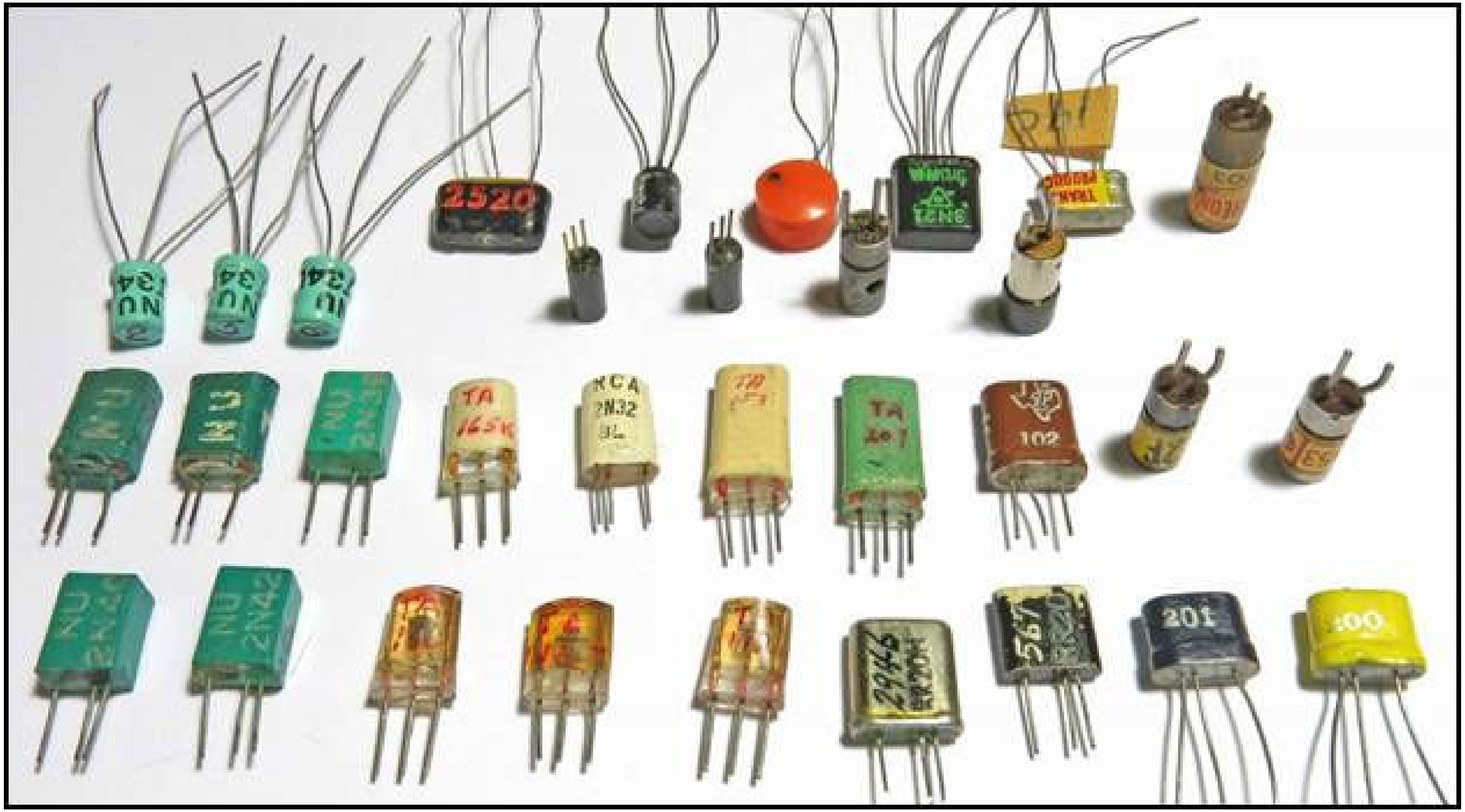
Transistor History – The Road To Silicon



Early point contact transistor case styles

Even so, lots of point contact transistors were manufactured!

Until Shockley's **revenge!**

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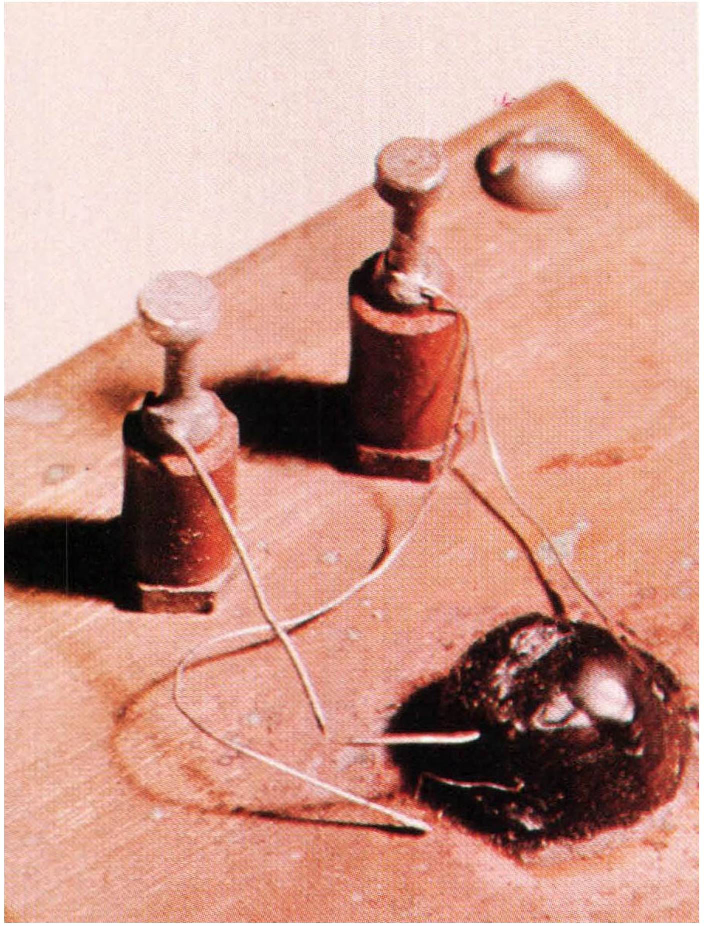
Transistor History – The Road To Silicon



- First junction device - April 12, 1950 – not a pretty sight!
- William Shockley’ revenge?
- Very slow speed
- Struggled even at audio!
- Morgan Sparks made significant speed improvements, January 1951 – capable of audio
- Bell announced functional, commercial design, July 1951
- The point contact transistor's dominant reign quickly ended

From such an ugly duckling, prettier things were born...

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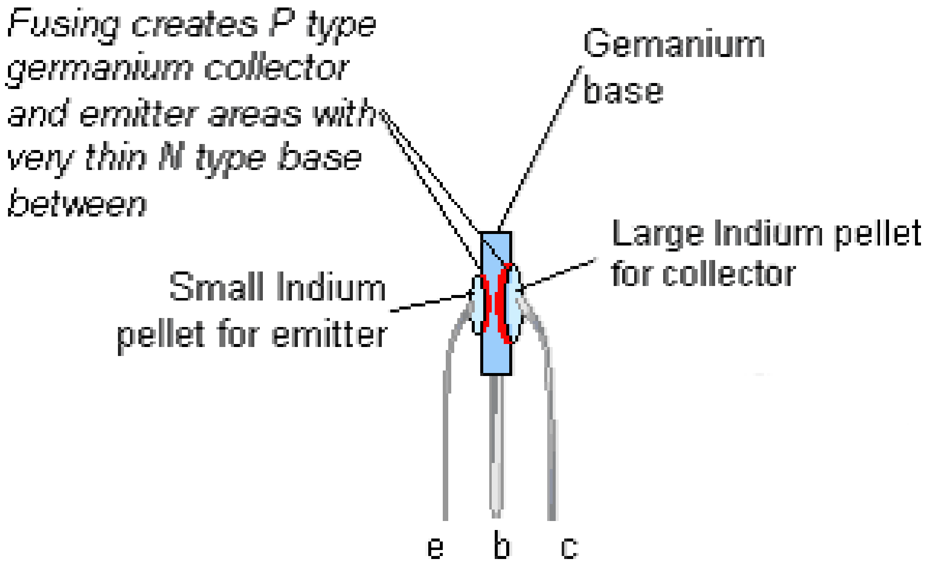
Transistor History – The Road To Silicon



- Early germanium junction transistor
- Fairly slow, audio types OC71, OC72, AC128
- Faster improvements occurred later
- OC44, FT < 15 MHz
- High Leakage Current
- Low Temperature < 70 C

But as if electrons weren't enough, what about photons?

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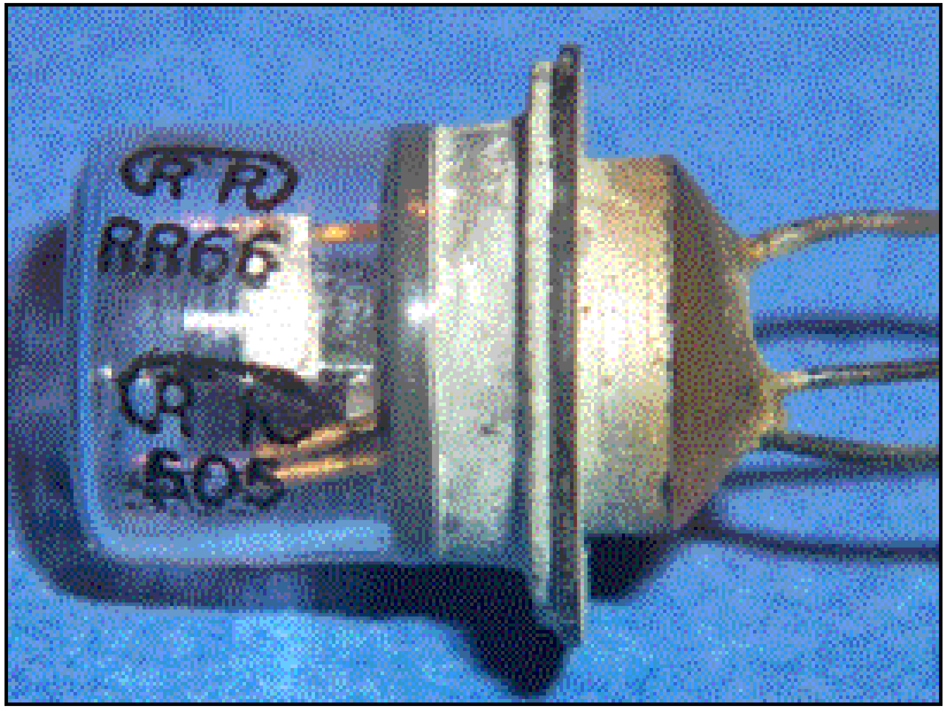
Transistor History – The Road To Silicon



- Many transistor variants soon followed
- Even photo-transistors were considered

← ***Early germanium photo-transistor***

The Germanium Bipolar Junction Transistor (Ge-BJT) was an immediate success!

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Transistor History – The Road To Silicon

Early junction transistor case styles

Efforts now began in earnest to make better, faster Ge-BJT devices...

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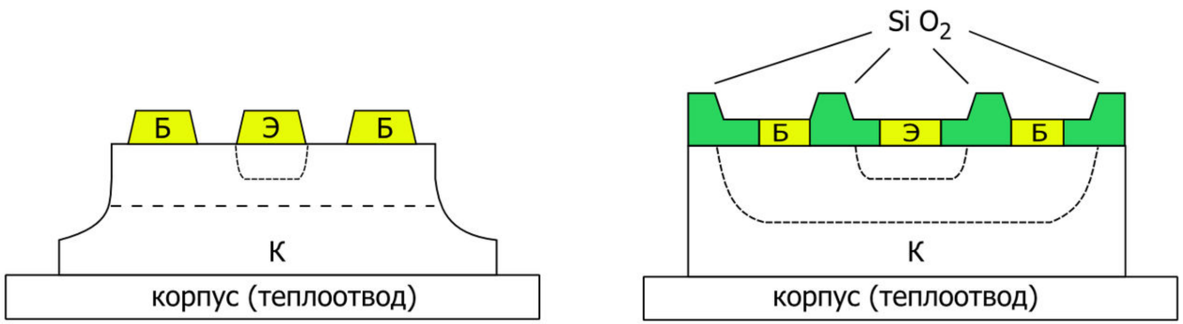
Transistor History – The Road To Silicon



- Early germanium junction transistors were slow
- High frequency operation was limited to 5 ~ 15 MHz – e.g. 0C44, 0C45
- Bell Labs developed the first prototype diffusion (mesa) transistors in 1954
- Early versions had FT ~ 60 MHz
- Similar RF performance to surface barrier

Simple junction Ge-BJT devices were soon augmented with many exotic geometries

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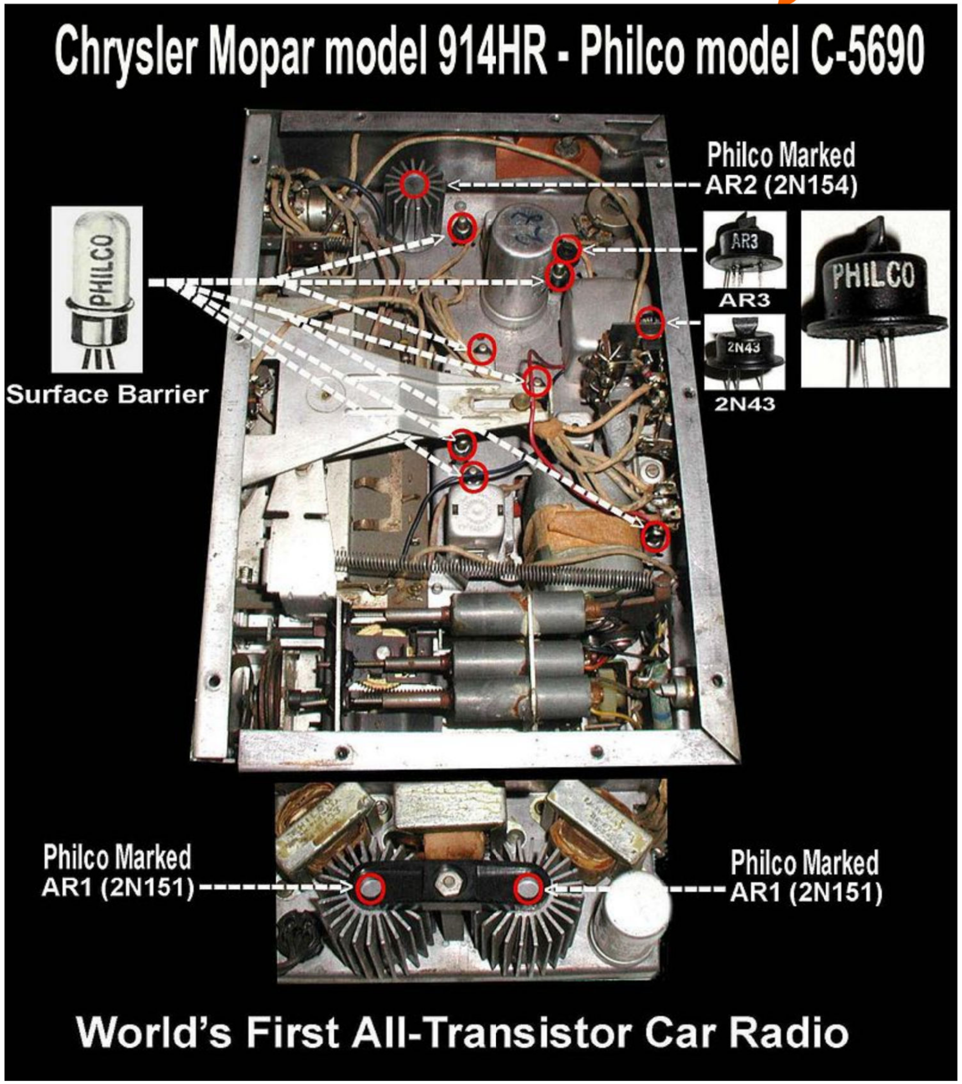
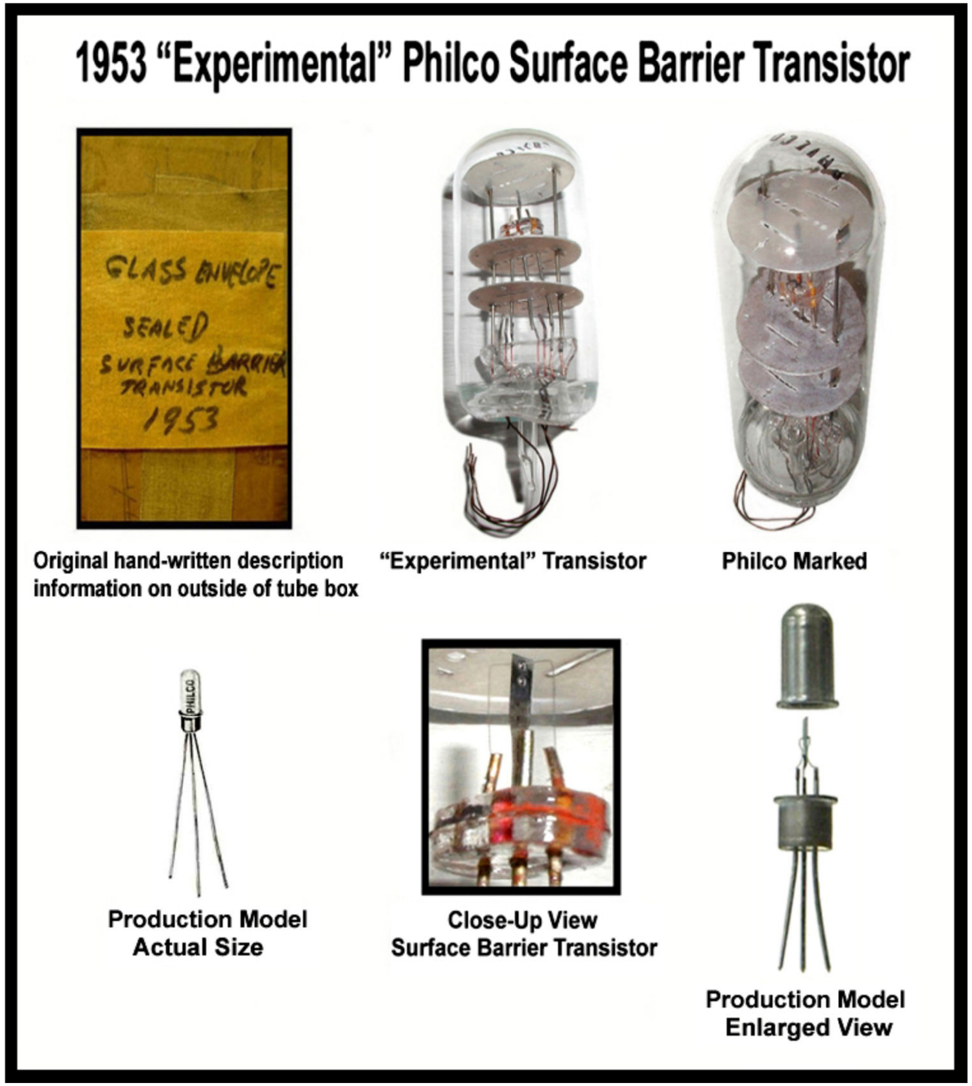
Transistor History – The Road To Silicon





The transistor revolution now attacks the perennial stronghold of the American vacuum tube!

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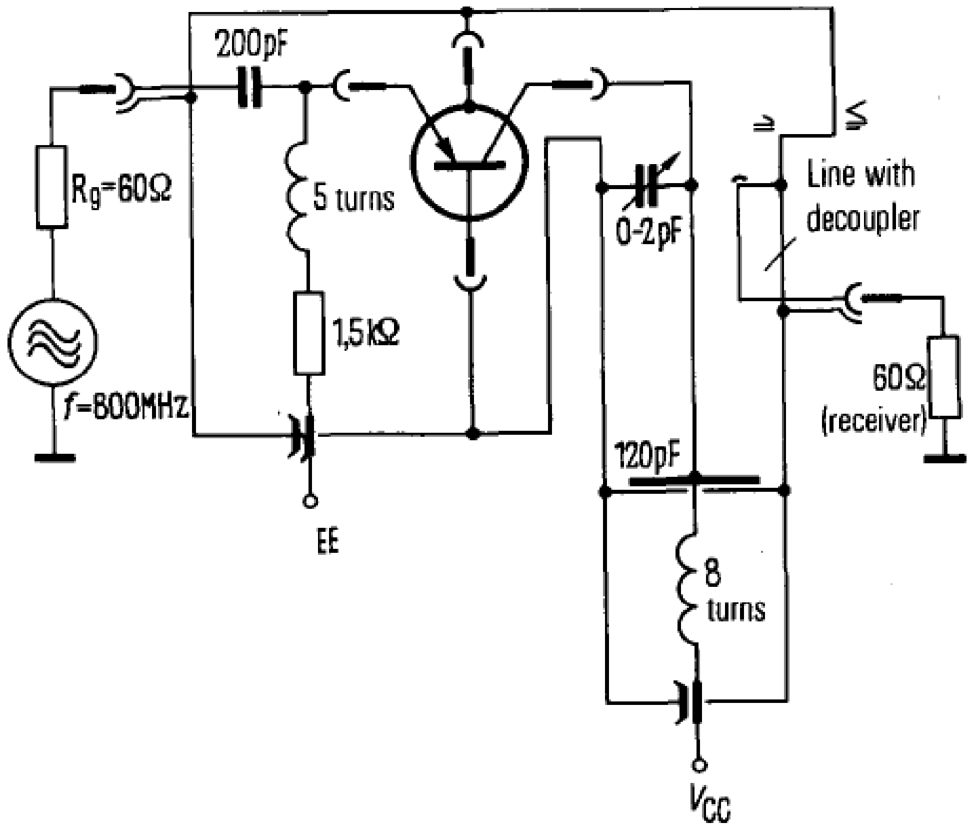
Transistor History – The Road To Silicon

Test circuit for power gain and noise figure at f = 800 MHz



- Useful frequency improvements soon followed
- Example AF239
- FT = 700 MHz
- 800 MHz RF Amplifier shown here operates above its FT!

The AF239 reached a pinnacle of Germanium BJT success – but what about Silicon?

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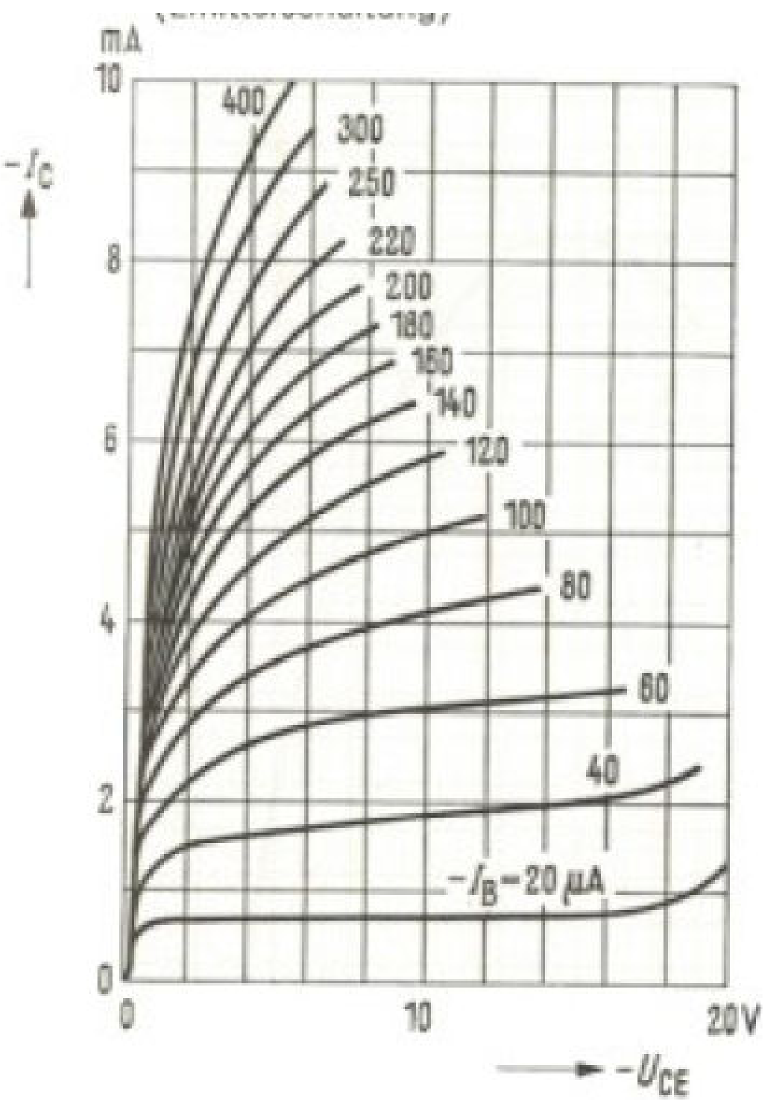
Transistor History – The Road To Silicon



- Example AF239 “Output Characteristics”
- Seldom used now
- No RF Prediction
- Better Models
- “S-Parameter”
- “Equivalent Circuit”

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Transistor History – The Road To Silicon

- Germanium failed at high temperatures
    - People looked at Silicon instead
- However purity was a major problem
- Silicon purity problem solved in 1954

"Morris Tanenbaum et al. at Bell Laboratories [33] were the first to develop a working silicon transistor on January 26, 1954"

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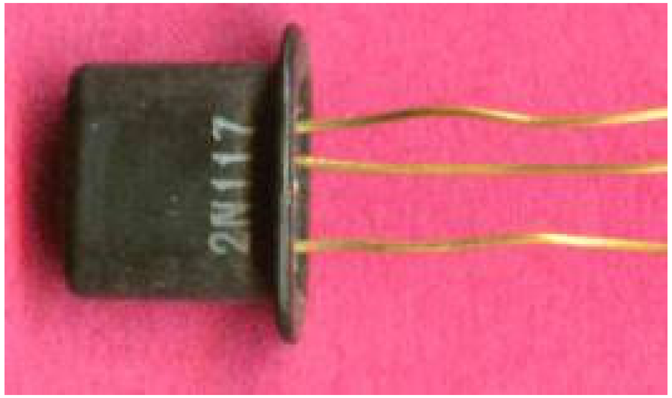
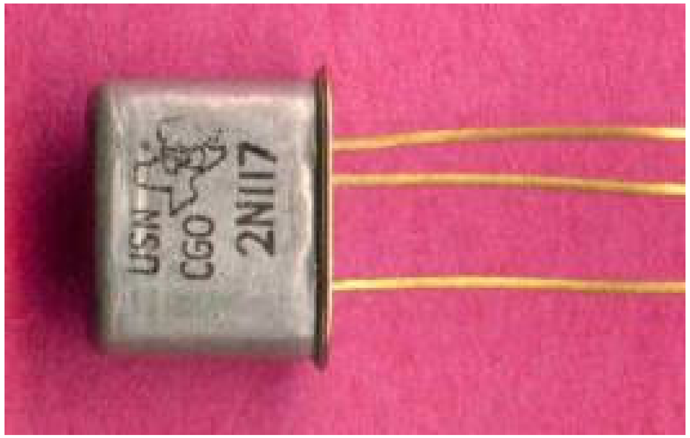
Transistor History – The Road To Silicon



Early Silicon Bipolar Junction Transistor (Si-BJT).



Achieved high temperature operation up to 175 C, but slow, very noisy

These copied the construction of early Ge-BJT. Could a better geometry be found?

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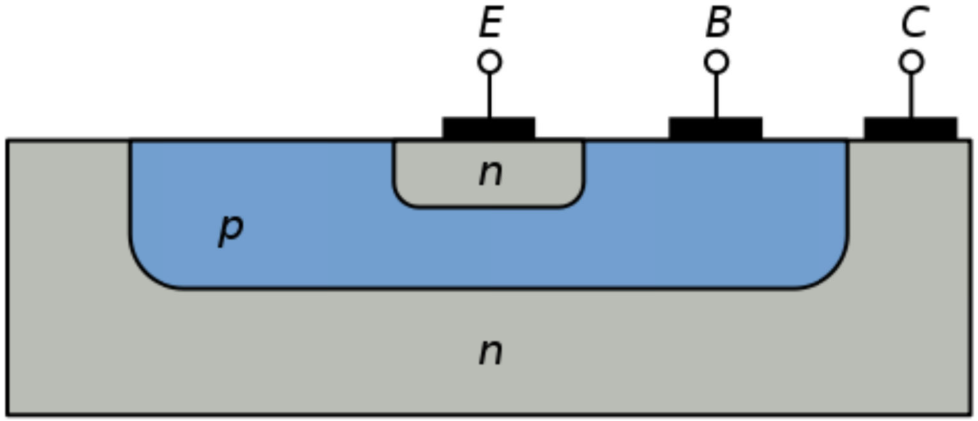
Transistor History – The Road To Silicon

- Junction silicon types were still slow, FT ~ 1 MHz.
- Solved by using a “planar geometry”
- Invented by Physicist Jean Hoerni, January 1959
- Used photographic processing
- BC549, BC559 etc use this
- Transition frequency (FT) up to 300 MHz at 10 mA



← ***Planar Transistor Structure***

First commercial planar transistor was the 2N1613 from Fairchild, April 1960. FT~60MHz, Ic < 500 mA

But where was the actual transistor in all this

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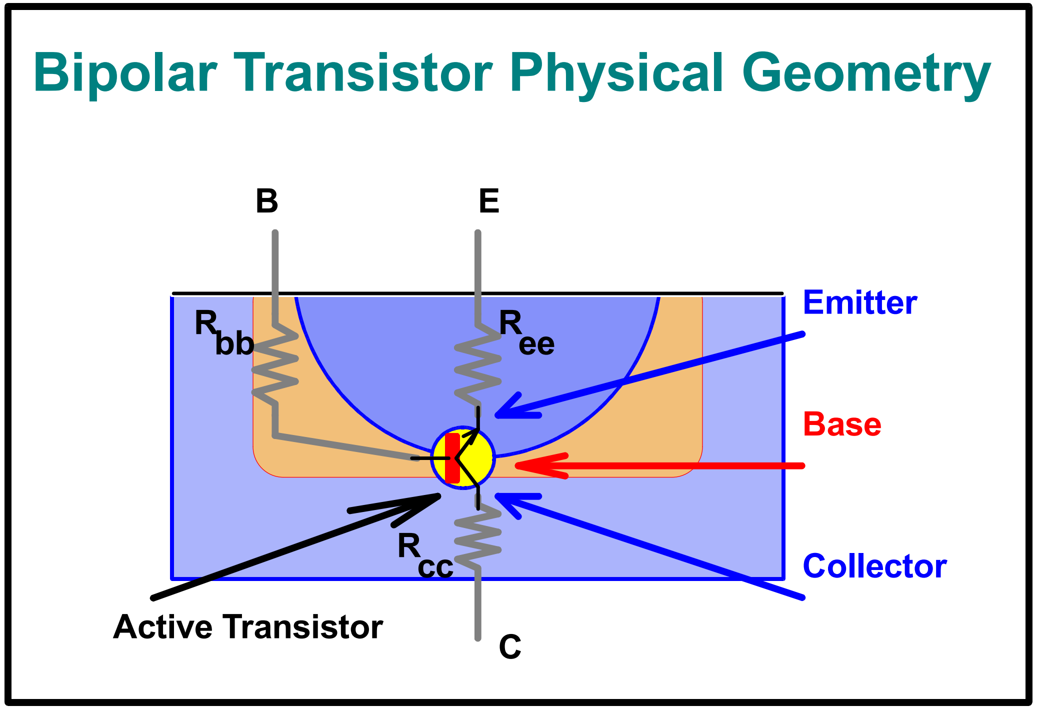
Transistor History – The Road To Silicon



- Photographic processes provided accurate junctions.
- Thin base region improved FT and current amplification H_{FE}
- Active transistor is buried
- Parasitic resistances called R_{bb}, R_{ee} and R_{cc}
- BC549, BC559 "base spreading resistance" R_{bb} ~ 200 Ohms
- BC549 Transition frequency (FT) up to 300 MHz at I_c = 10 mA

← ***Planar Transistor DC Model***

How could these parasitic resistances be reduced?

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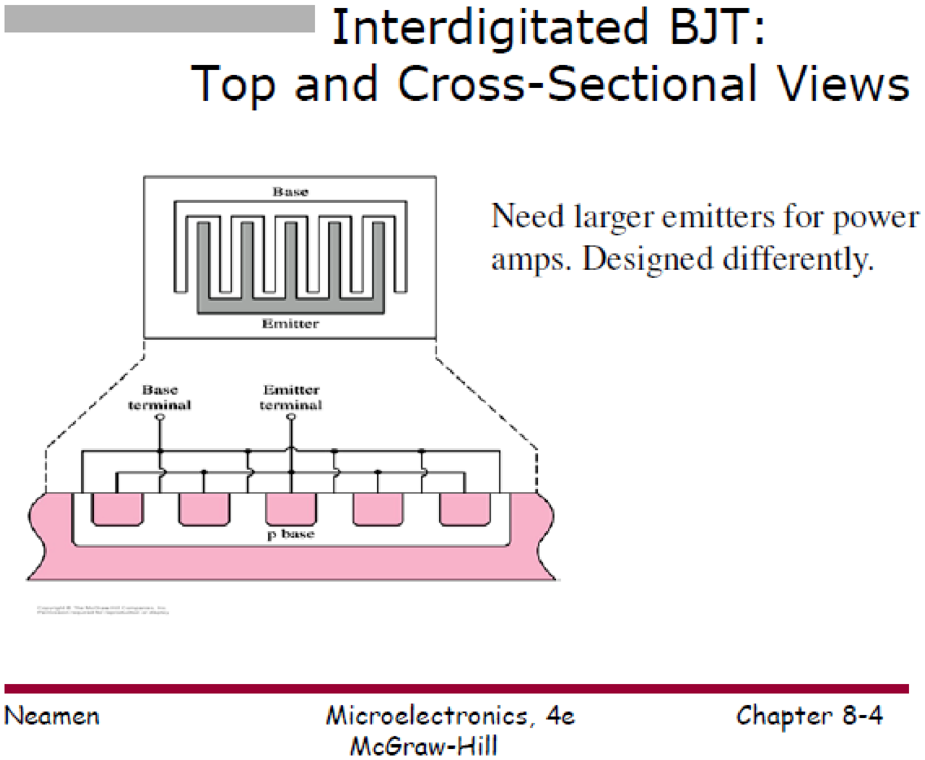
Transistor History – The Road To Silicon



- Highest frequency limited to about FT ~ 1.2 GHz (e.g. BFY90, BFS17)
- Single transistor area too large – high capacitance
- R_{bb} too high – forms a low pass filter (LPF) with C_{be}
- Solution to place many smaller transistors in parallel - “interdigitated” multiple-emitter
- BFR90, BFR91, BFR92
- Upper frequency 5 GHz

How much better were such interdigitated devices?

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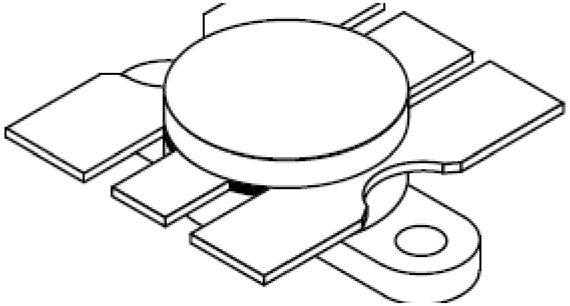
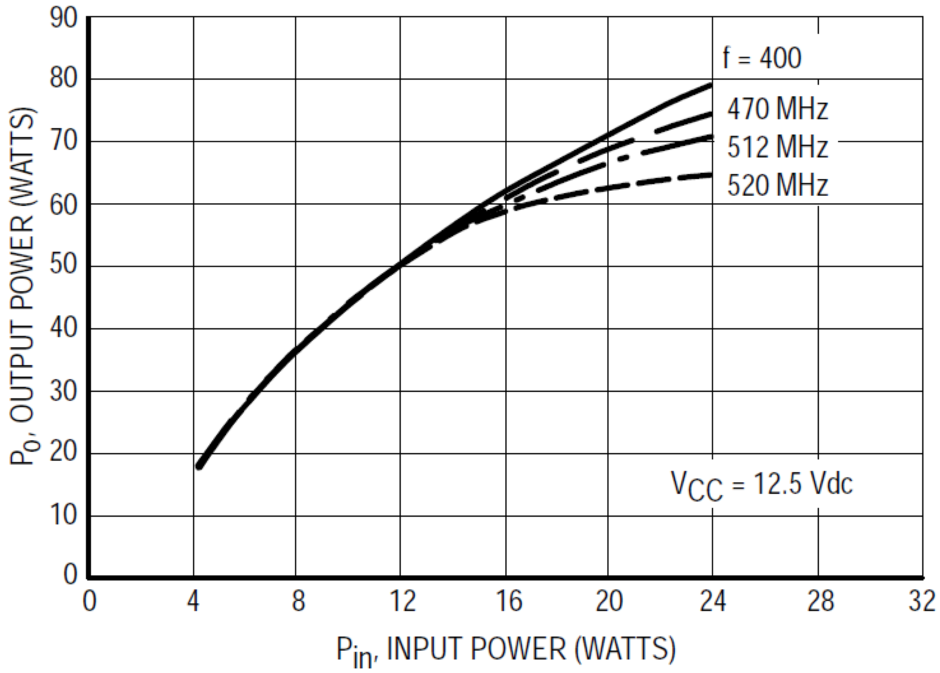
Transistor History – The Road To Silicon



Guaranteed 440, 470, 512 MHz 12.5 Volt Characteristics
Output Power = 50 Watts
Minimum Gain = 5.2 dB @ 440, 470 MHz
Efficiency = 55% @ 440, 470 MHz



- MRF650 – Pinnacle of **RF Power** BJT Technology
- Extremely low power gain
- Needed carcinogenic beryllium oxide mount disk
- Expensive, inconsistent
- Obsoleted by Motorola' LDMOS about 10 years ago
- All major manufacturers withdrew R&D with 1 year
- RF Power BJT Only for Service

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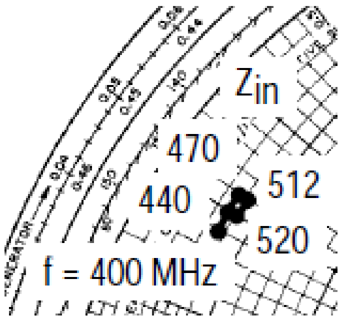
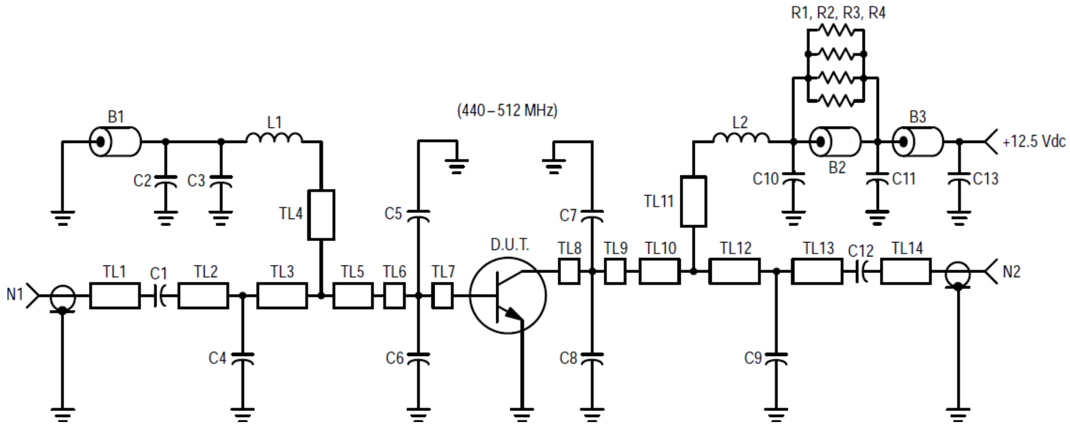
Transistor History – The Road To Silicon

f (MHz)	Z_{in} Ω	Z_{OL}* Ω
400	0.7 + j2.8	1.4 + j2.3
440	0.7 + j3.2	1.1 + j2.6
470	0.8 + j3.3	0.8 + j2.7
512	0.8 + j3.2	0.7 + j2.9
520	0.7 + j3.0	0.6 + j3.0





- MRF650 – Extremely low input and output impedances
- Impedances strongly frequency dependent (excessive match "Q")
- Zero bias operation (FM)
- Prone to parametric instability / VSWR / Temperature / Voltage / Drive Power / Poor Reproducibility

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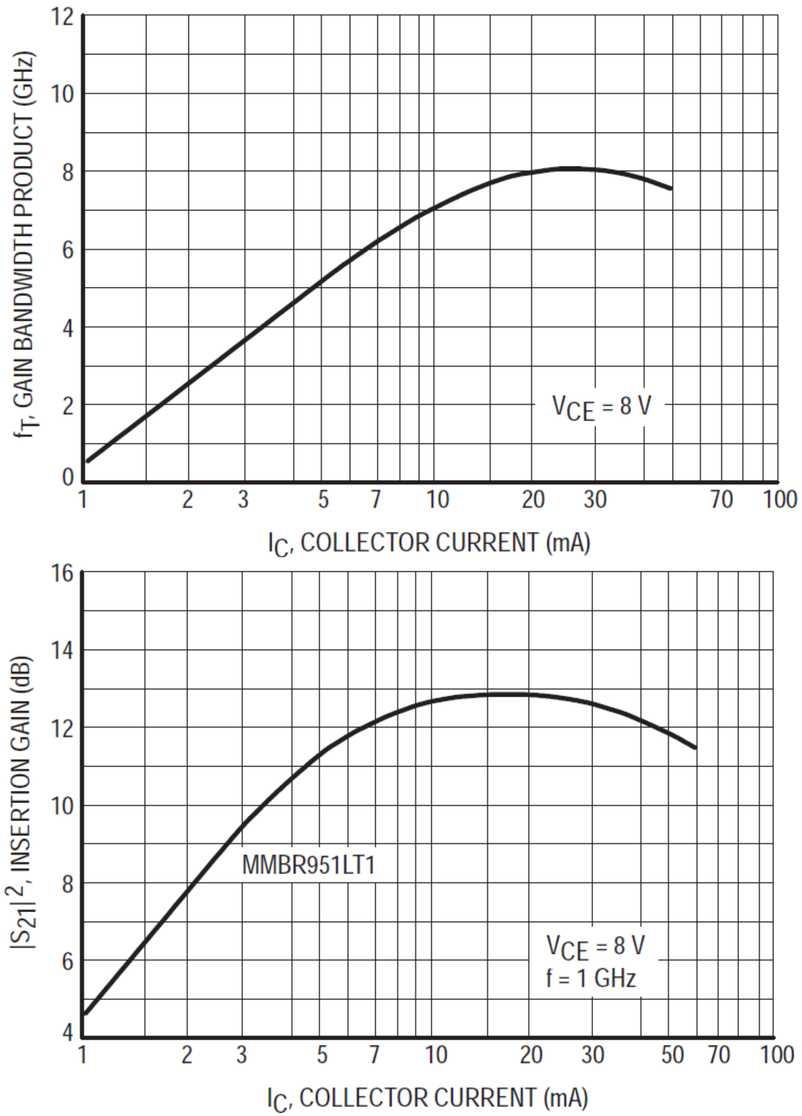
Transistor History – The Road To Silicon



- Philips retained 5 GHz BJT for decades – no progress
- Motorola made small improvement with "arsenic implanted emitters" - MRF571, MMBR951
- FT improved to 8 GHz
- 18 finger 1.25 Micron
- Used in T800, T2000 series
- Power gain $|S_{21}|^2$ follows FT
- FT scale is linear, log (dB) $|S_{21}|^2$

But was 8 GHz really enough?

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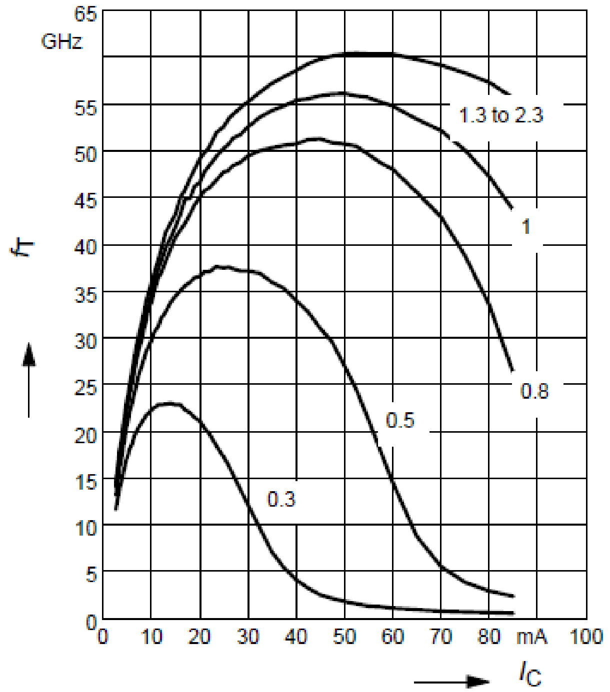
Transistor History – The Road To Silicon

8 GHz too slow! People considered “composite semiconductors” - Infineon, ex Philips, introduced first SiGe BJT, BFP620, FT ~ 60 GHz, $US 1.00

Transition frequency $f_T = f(I_C)$

f = 1GHz

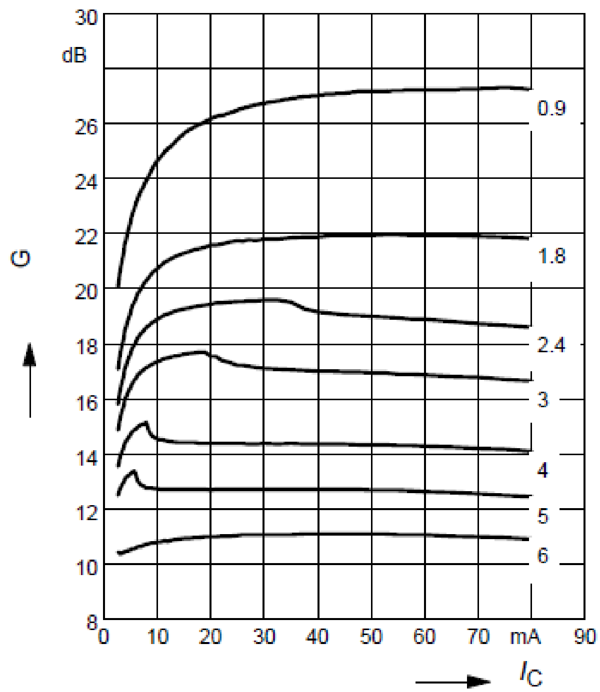
V_{CE} = Parameter in V



Power gain G_{ma}, $G_{ms} = f(I_C)$

V_{CE} = 1.5V

f = Parameter in GHz



Composite semiconductors soon became the new black!

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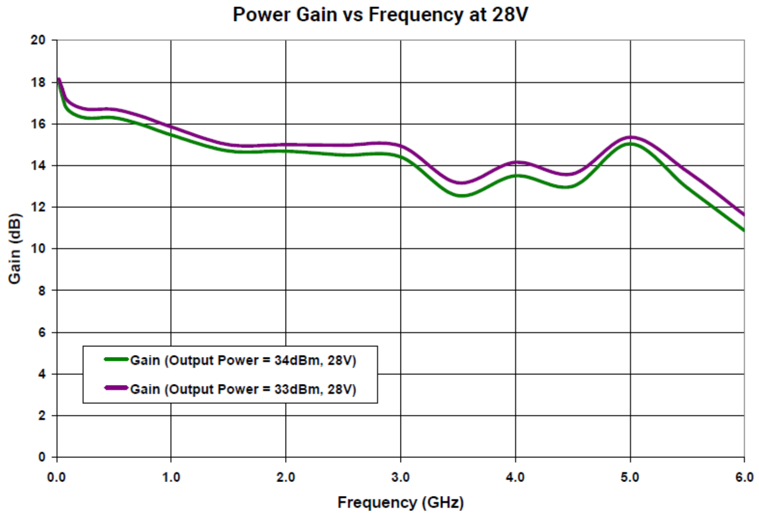
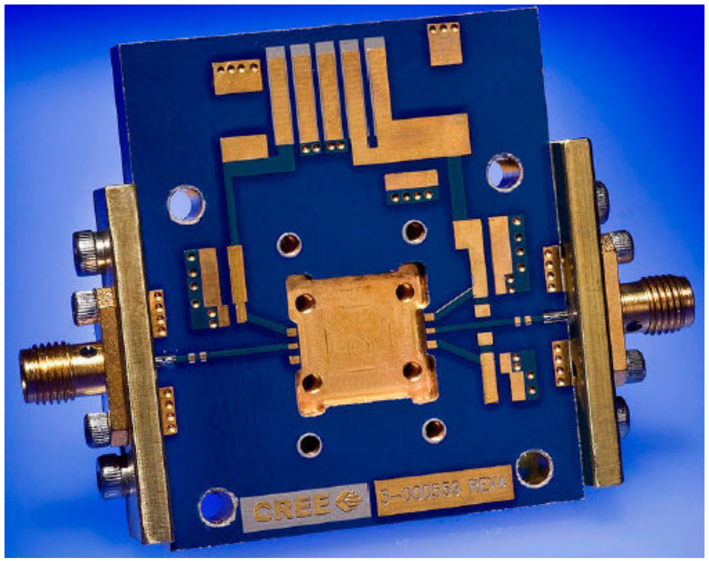
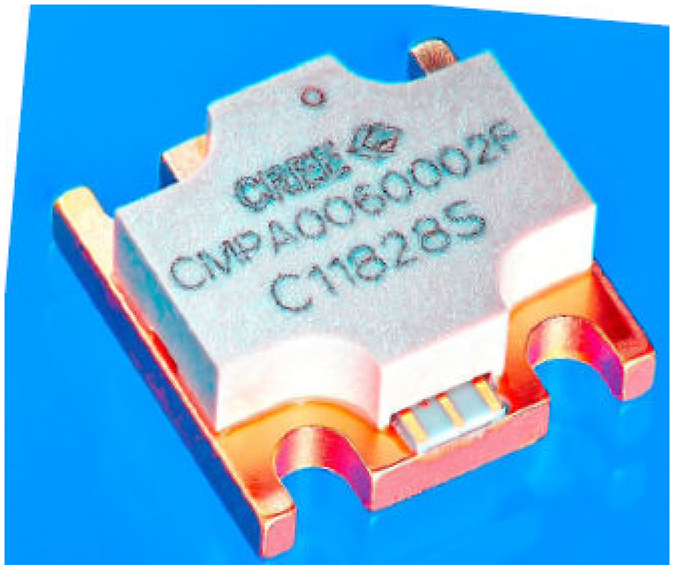
Transistor History – The Road To Silicon



- Composite semiconductors emerged
- Silicon Germanium SiGe very popular
- Many RFIC use SiGe – e.g. WiFi
- Other composites also common now – e.g. Cree Gallium Nitride (GaN) microwave device





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Transistor History – The Road To Silicon

We now have many varied transistor types

- Unijunction Transistor – Relaxation Oscillator < 1 MHz - largely obsolete
- Silicon Controlled Rectifier (SCR) – Very High Voltage / Current – Mature, Popular
- TRIAC "Triode for AC" – AC Switch – Light Dimmers - Mature, Popular
- Junction Field Effect Transistor (JFET) – Seldom Used – Eventual Obsolescence
- **Metal Oxide Field Effect Transistor (MOSFET) – Extremely Popular**
- **Insulated Gate Bipolar Transistor (IGBT) – MOSFET + BJT – Very Popular**
- **Lateral Diffused MOSFET (LDMOS) – 1 GHz, 1 kW – Mature - Very Popular**
- Metal Silicon FET (MESFET) – Small Signal Microwave – Loosing Favor
- Gallium Arsenide FET (GASFET) – Class A, V_{ds} < 10V - Loosing Favor
- **Gallium Nitride High Electron Mobility Transistor (GaN HEMT) – 6 - 20GHz, LNA and HPA 6GHz 350W – Receiving Extensive R&D – Increasing Popularity**

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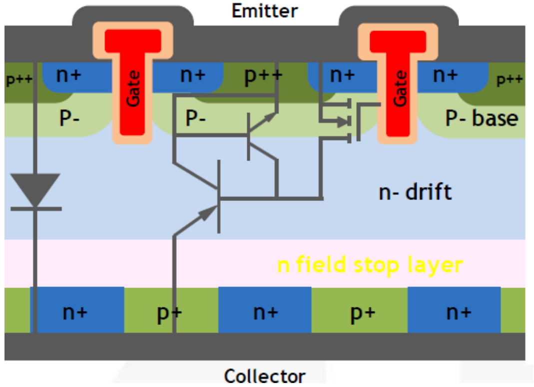
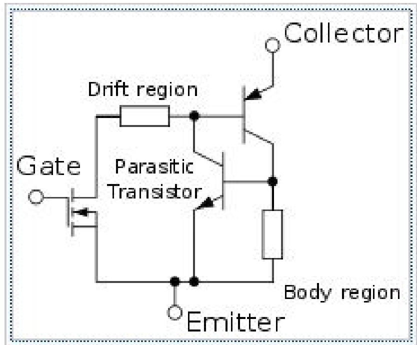
Transistor History – The Road To Silicon





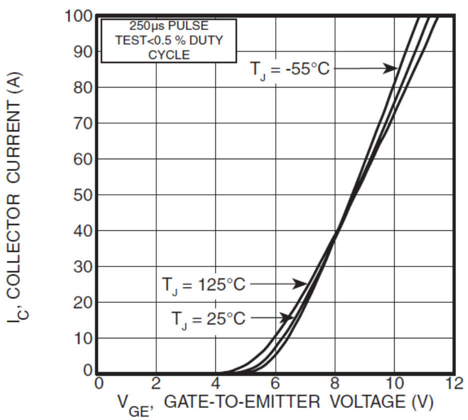
Equivalent circuit for IGBTs

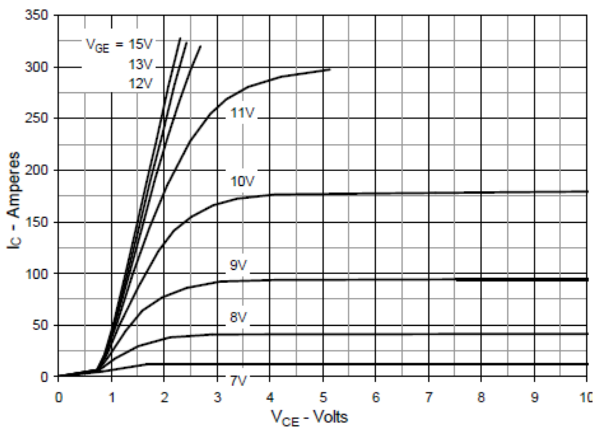
Insulated Gate Bipolar Transistor

IGBT

MOSFET input, common collector PNP BJT Output

IXXK300N60B3





- Ex. 600 V 300 Amp
- Switch to 100 kHz
- Speeds approach fast MOSFET
- Perhaps 80m RFPA

Bipolar Junction Transistor

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2. BJT Electrical Characteristics – 35 minutes

To understand these characteristics we first need to know how the BJT works!

This section will use explanations based on concepts and analogies with familiar items – not a I.E.E.E. document or PhD Thesis!

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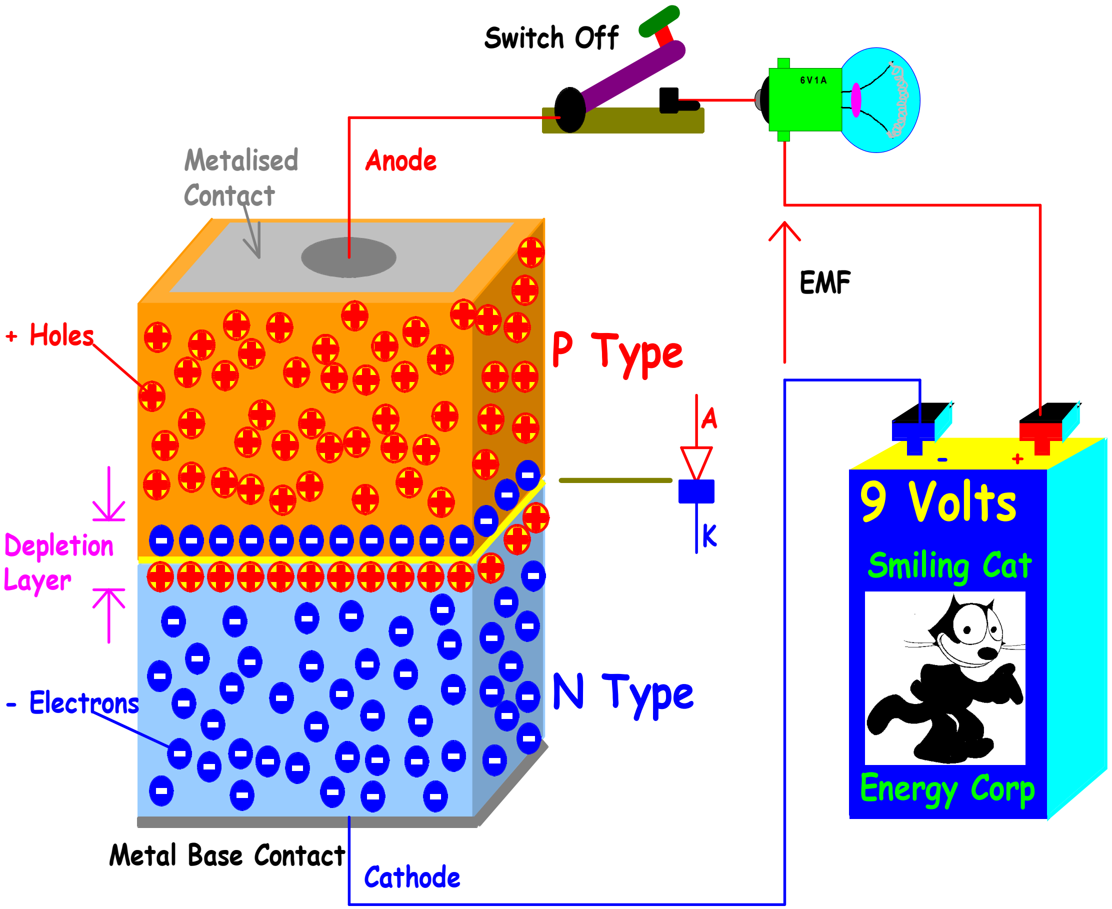
Electrical Characteristics

Unbiased Junction Diode Depletion Layer



- The BJT begins with the <u>diode junction</u>
- Diodes Have connected "P" and "N" junctions
- P Material has "holes"
- N Material has "electrons"

Switch open – no movement across the "depletion layer"

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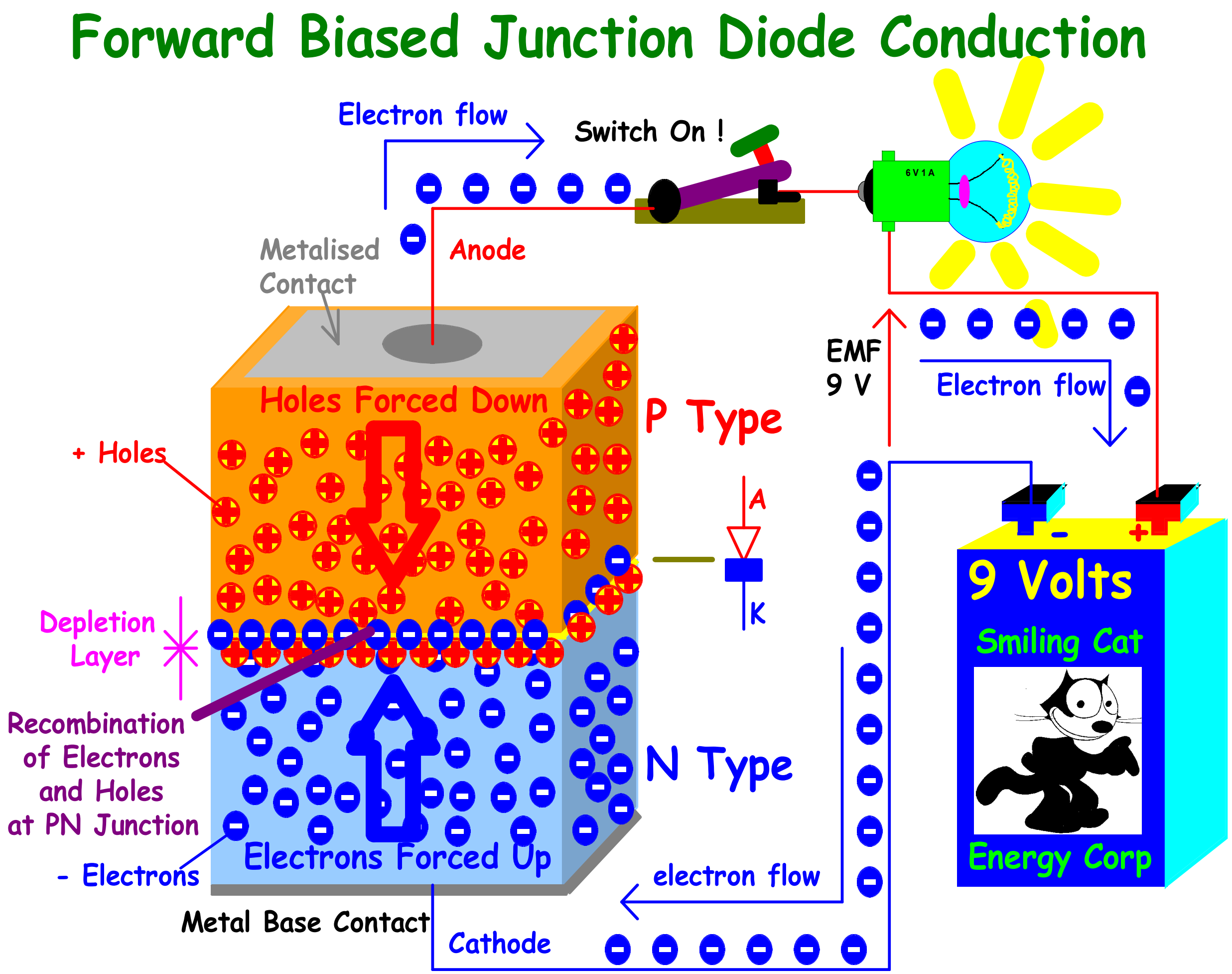
Electrical Characteristics



- **Close switch, current flows, light glows!**
- **+ Holes repelled downwards by Vs+**
- **– Electrons repelled upwards by Vs-**
- **Charges combine in the depletion layer**

Switch closed – charges combine in the depletion layer

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Electrical Characteristics

- **Why does Electron-Hole (re)combination cause current flow?**
- **Explanation by simple analogy**
- **Consider a cloud-sea-leaky cave analogy**

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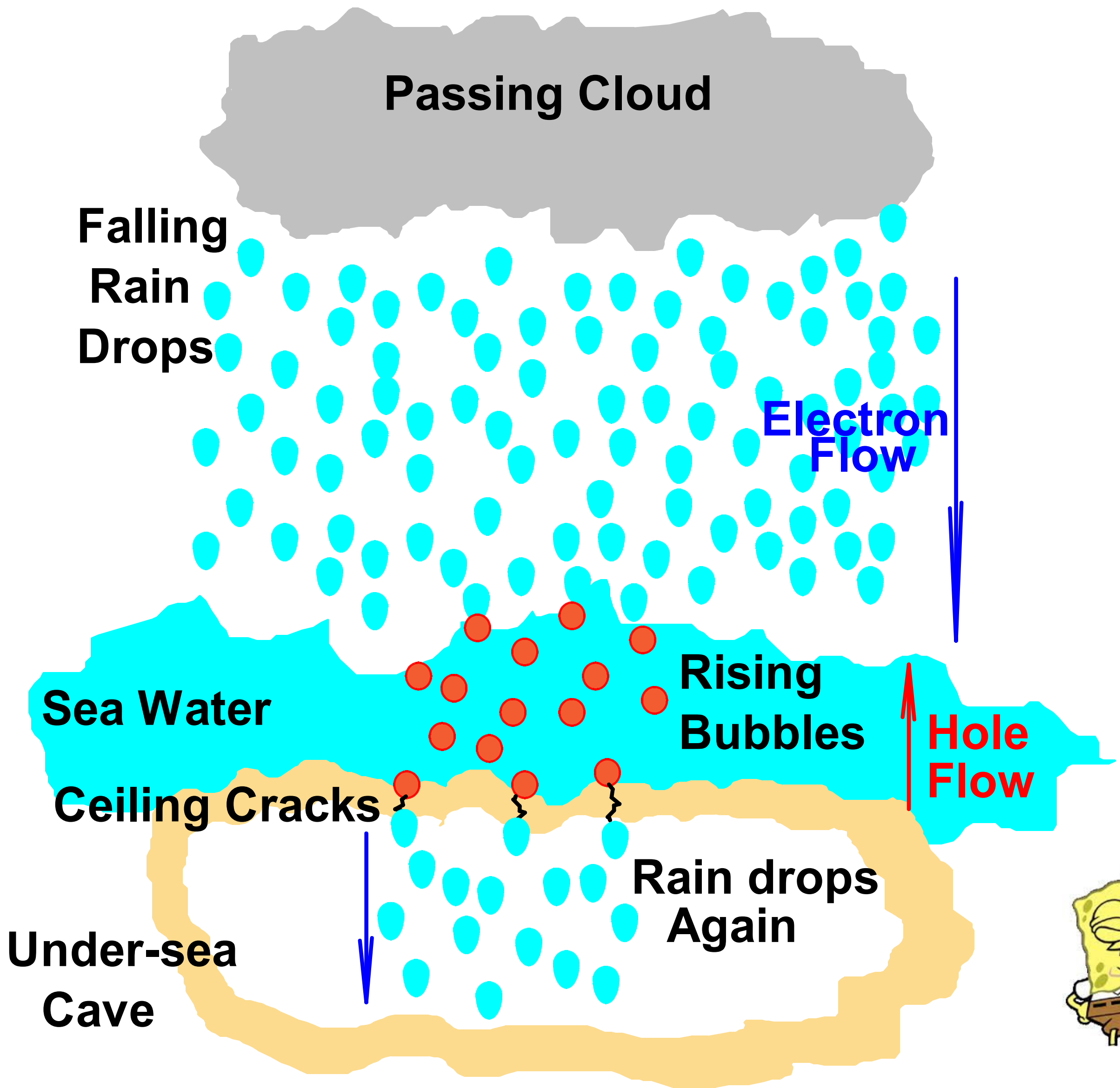
Electrical Characteristics



- Rain (electrons) come from a passing cloud
- Water drips from cracks in the cave
- For each drip (electron) a rising bubble (hole) is formed

Holes and electrons then (re)combine

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Electrical Characteristics

Bipolar Junction Transistor – BJT – 2 Junctions

Two versions – NPN and PNP

NPN Examples – BC549, 2N2222, BRY90, BFR91

PNP Examples – BC557, 2N2905, TIP42C, AD162

So how does the BJT work? - Use NPN as an example

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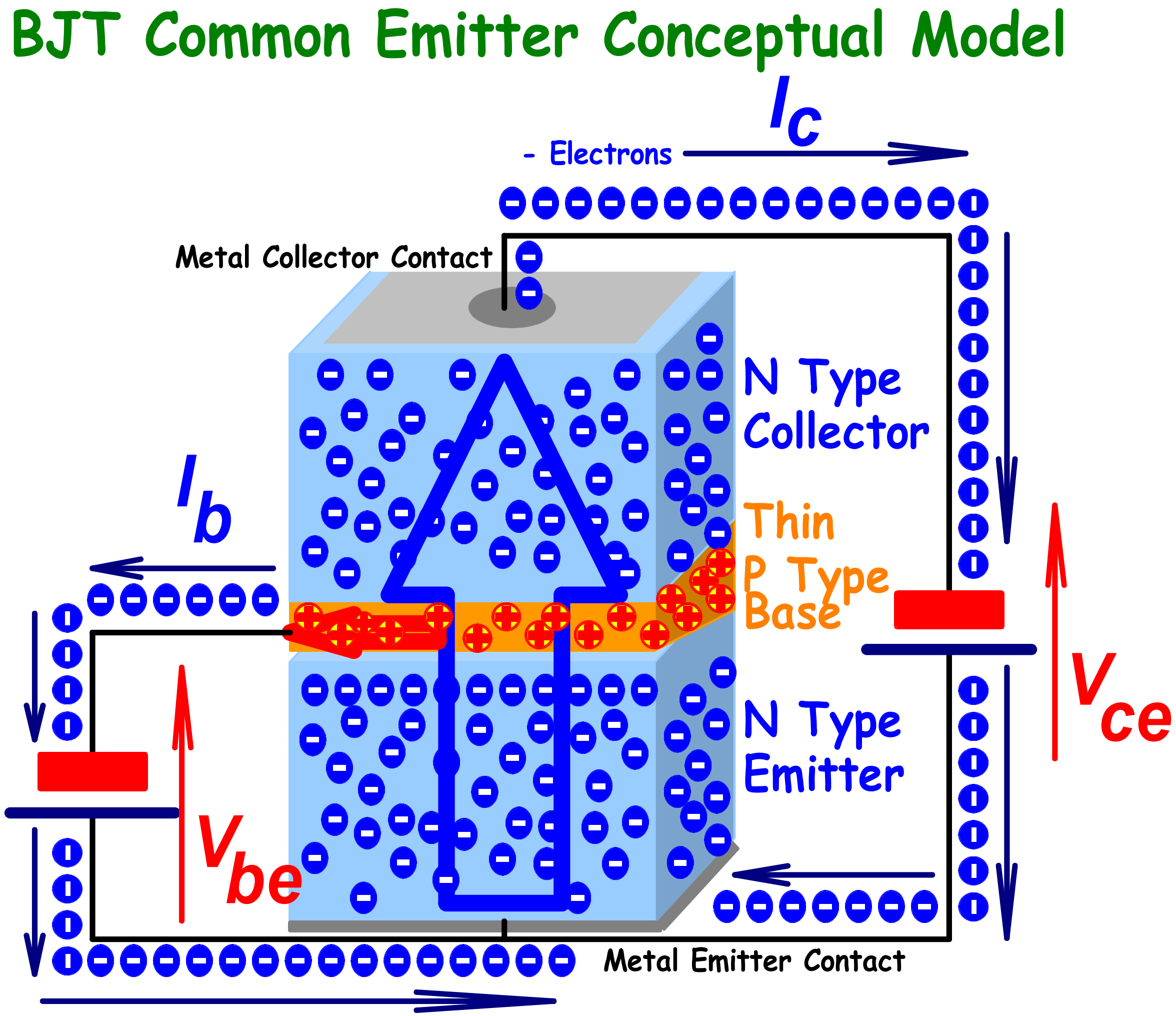
Electrical Characteristics



- V_{be} attracts electrons from the emitter
- Most fly through the thin P-Type Base
- V_{ce} attracts these as *Ic*
- Leakage holes form I_b
- V_{be} attracts these as leakage electrons I_b

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Electrical Characteristics

This "Physical Model Concept" has several "Electrical Model" interpretations

- ***Current Controlled Model – uses "h parameters" - suits audio***
- ***Transconductance Model* – uses "*y parameters*" - mid RF**
- ***Scattering Model* – uses "*s parameters*" - suits all**
- **All are equivalent and translations only require algebra**

Static VI Characteristics, although interesting, are seldom if ever useful in BJT amplifier design. Therefore I will focus only on dynamic characteristics

S – parameters were originally developed by microwave engineers as BJT devices tended to be unstable in equipment used to measure *h* or *y* *parameters* (h_{ie}, h_{fe}, h_{re}, h_{oe} *and* y_{ie}, y_{fe}, y_{re}, y_{oe})

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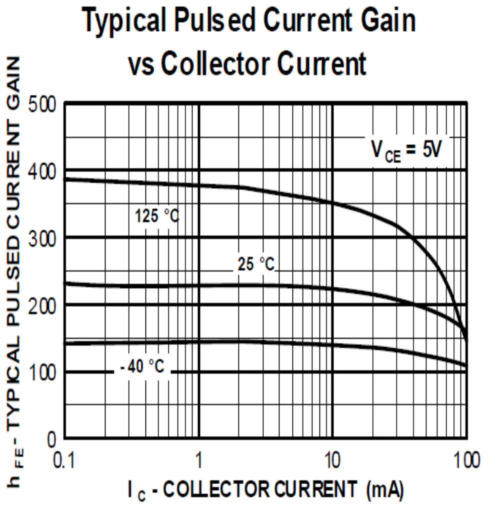
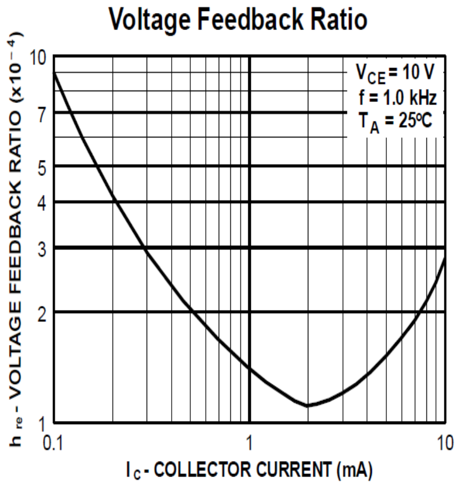
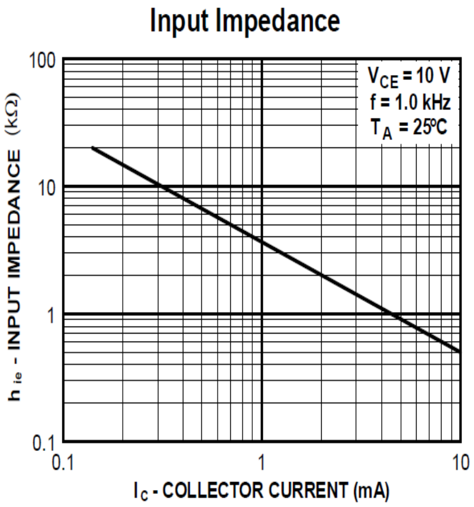
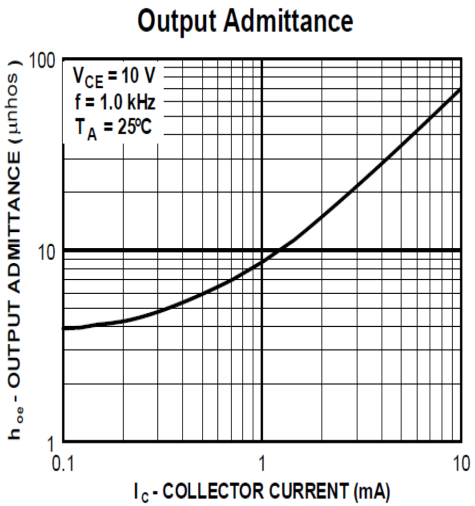
Electrical Characteristics

Example – 2N3904 Legacy NPN Audio BJT – h_{fe}, h_{re}, h_{ie} and h_{oe}









- h_{xx} – parameters - estimate amplification potential
- h_{fe} depends on temperature and collector current I_c
- Reciprocal of h_{re} indicates maximum possible voltage gain
- h_{ie} falls as I_c increases
- h_{oe} indicates output resistance

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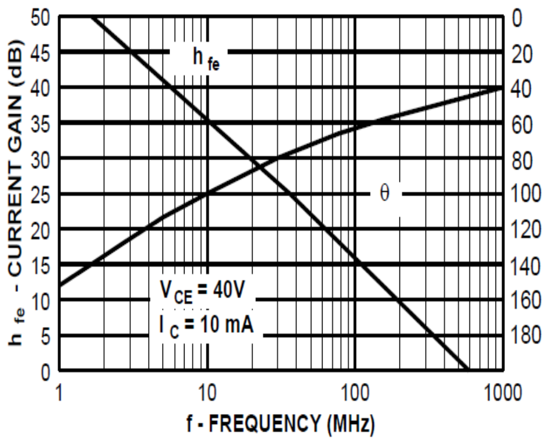
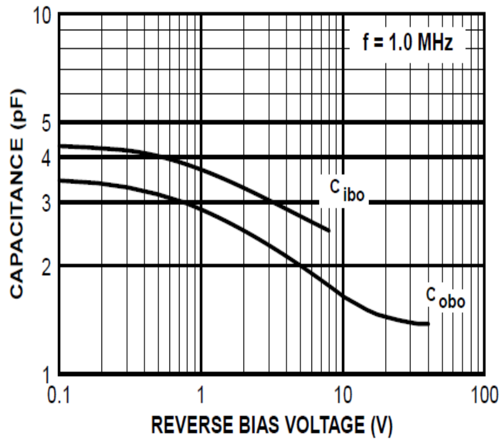
Electrical Characteristics

Example – 2N3904 Legacy NPN Audio BJT – Frequency Behavior

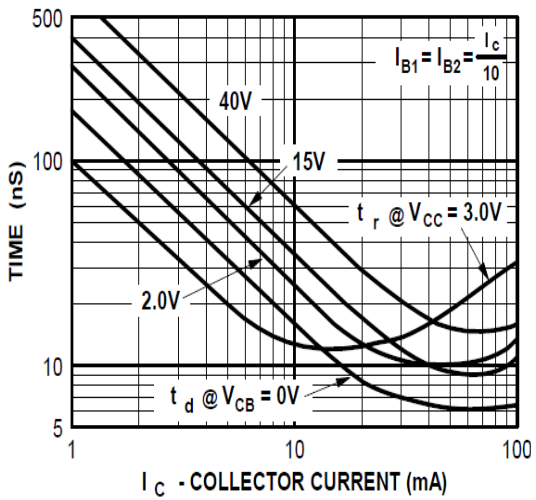
Current Gain and Phase Angle vs Frequency



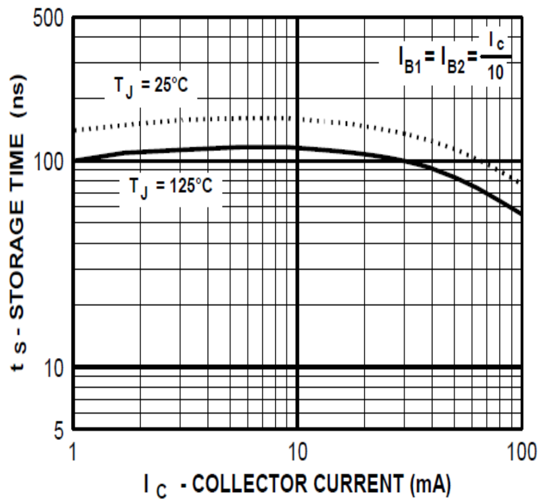
Capacitance vs Reverse Bias Voltage



Turn-On Time vs Collector Current



Storage Time vs Collector Current

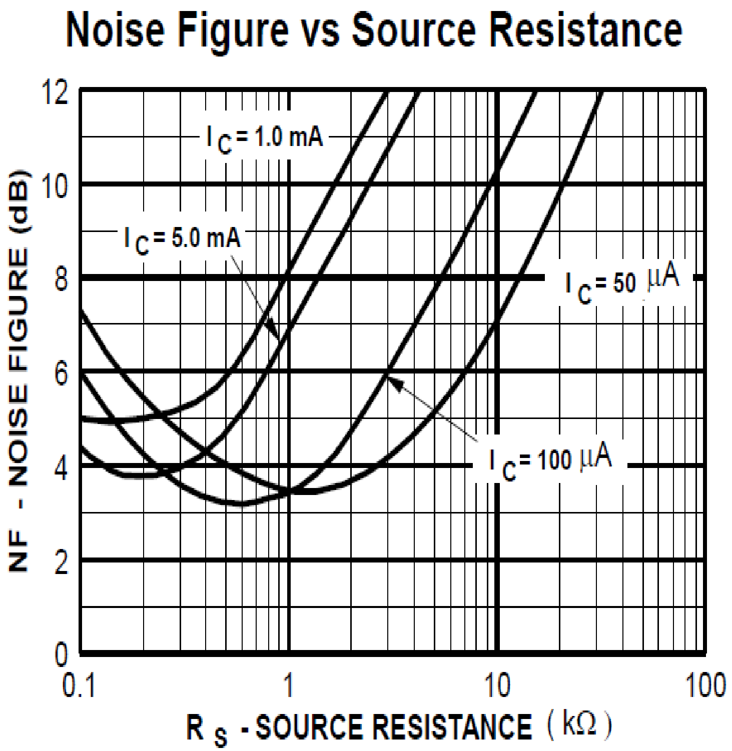


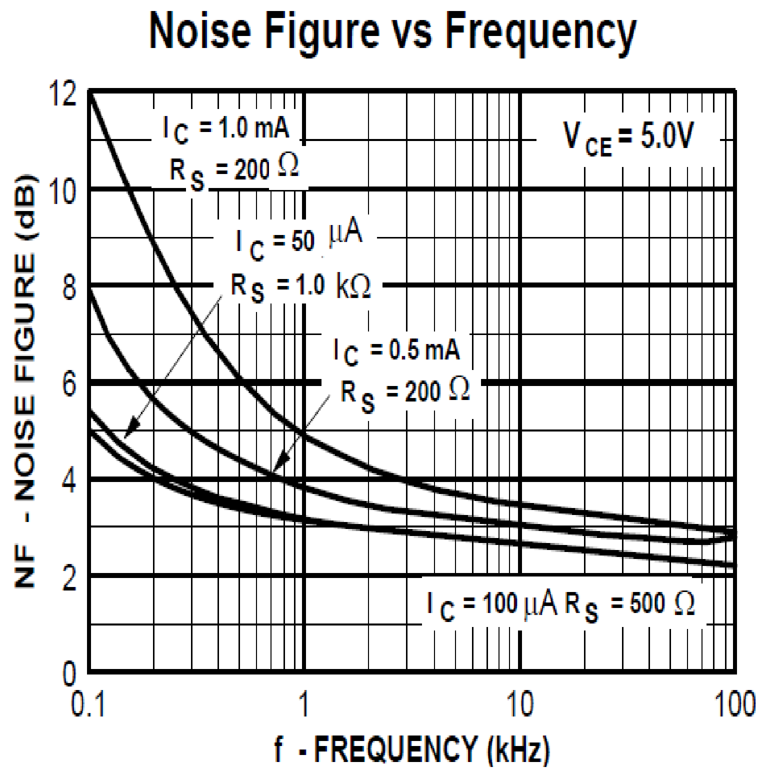
- Transition frequency FT is defined as h_{fe} = 1 (0 dB)
- FT is largely dependent on device base-emitter C_{ibo}
- Large signal switching times only loosely depend on FT
- Turn on time ton depends on *Ic* and *Vce*
- The BJT Achilles heal is "storage time" t_s
- Storage time t_s dominates

BJT

Electrical Characteristics

Example – 2N3904 Legacy NPN Audio BJT – Noise Behavior

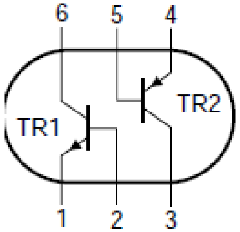


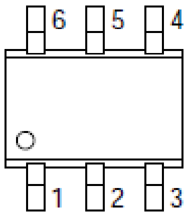


- **All components introduce noise. BJT noise has an optimum for I_c and R_s**
- **Note another Achilles heal – Flicker / shot noise – increases at low frequencies with an excess rate approximately $^1/_f$ usually starting below 1 kHz**

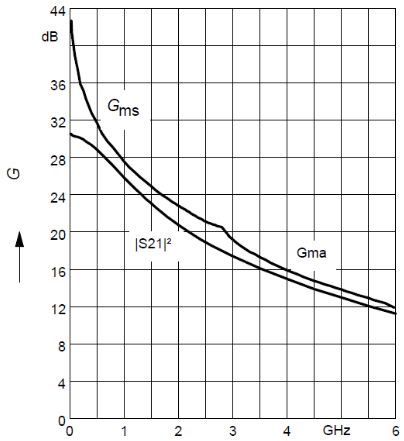
BJT

Electrical Characteristics



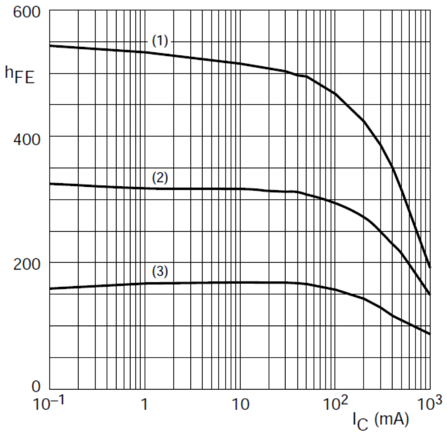


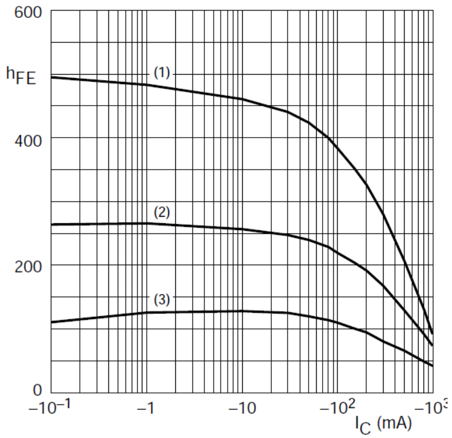
Dual NPN-PNP BJT
BFP520 SiGe right
BFP740 SiGe below
45GHz 50 mA $1:52

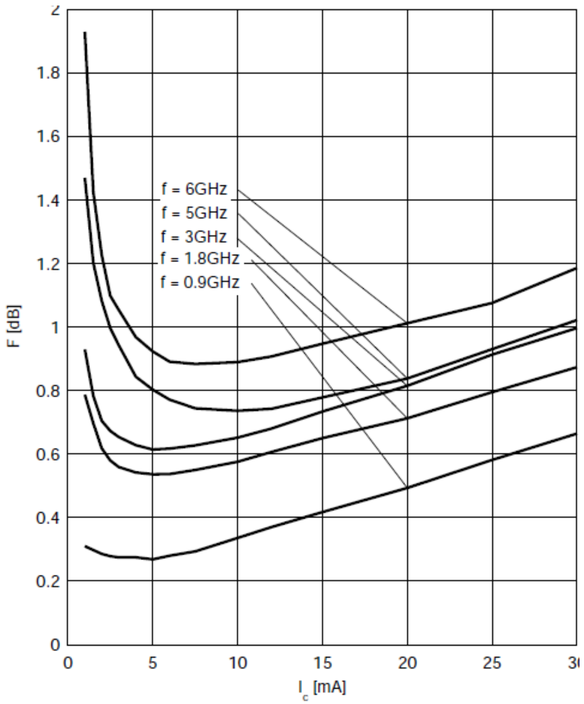


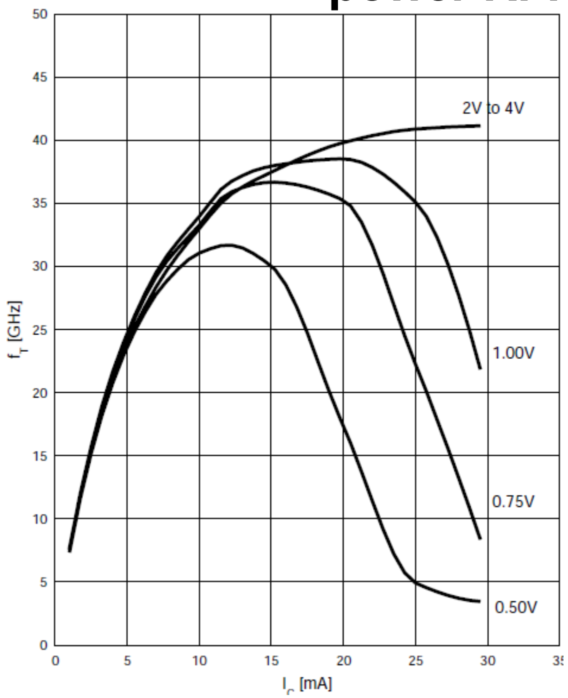
Bipolar SiGe BJT

Extremely popular, inexpensive, RF LNA, microwave, low V_{ce}, best I_c = 150mA, but not suitable for high power RFPA









Good NF

High Gain

Simple

matching

One supply

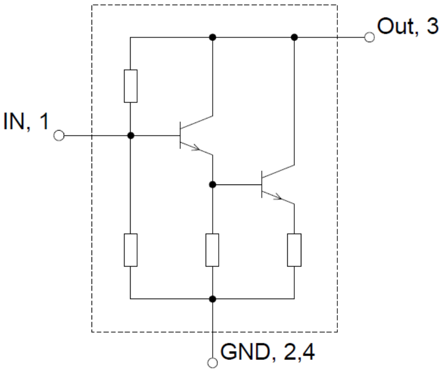
Main RFIC

component

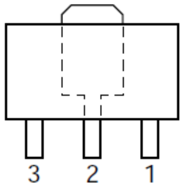
Inexpensive

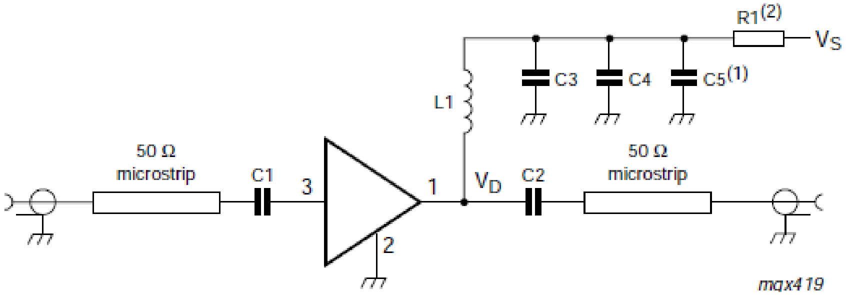
BJT

Electrical Characteristics



BGA616 - SGA6589





Typical MMIC circuit
Microstrip optional

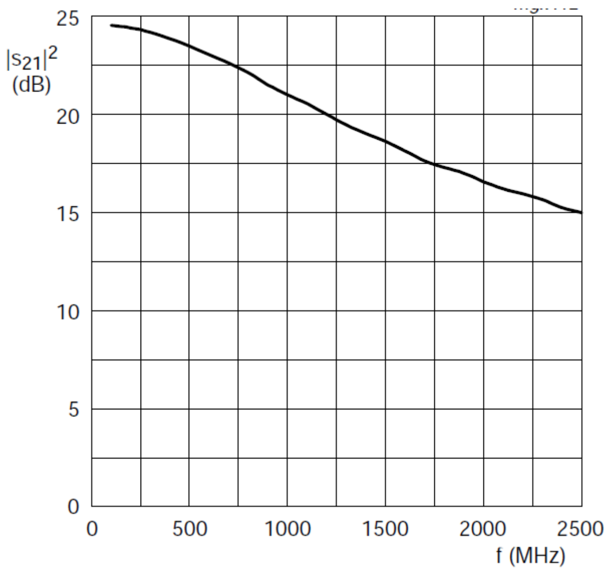
MMIC "Gain Blocks"

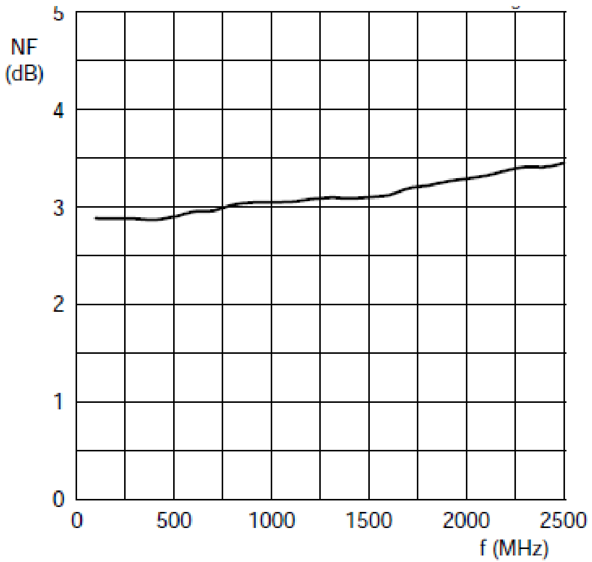
50 Ohms input / output

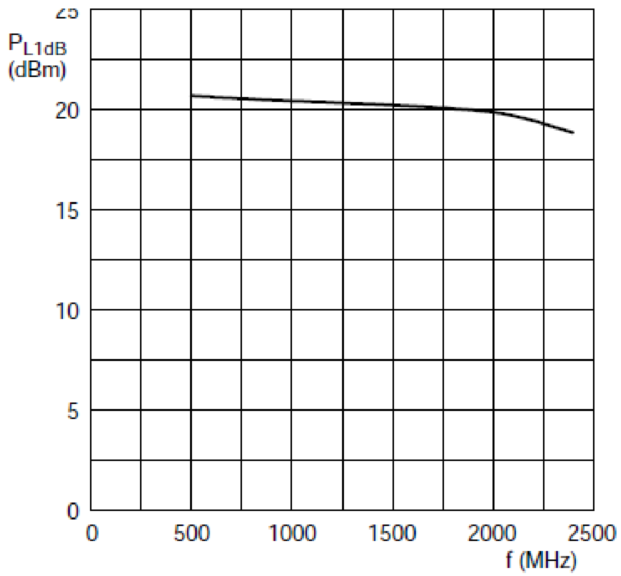
Wideband, NF not bad

One supply, simple bias

SGA6589 20dBm $2:48



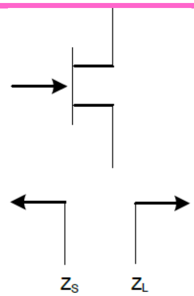


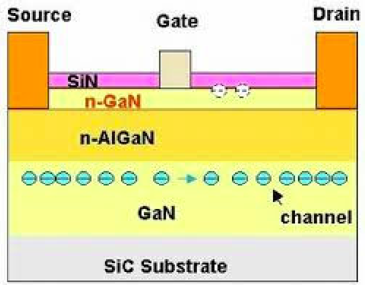


BJT

Electrical Characteristics

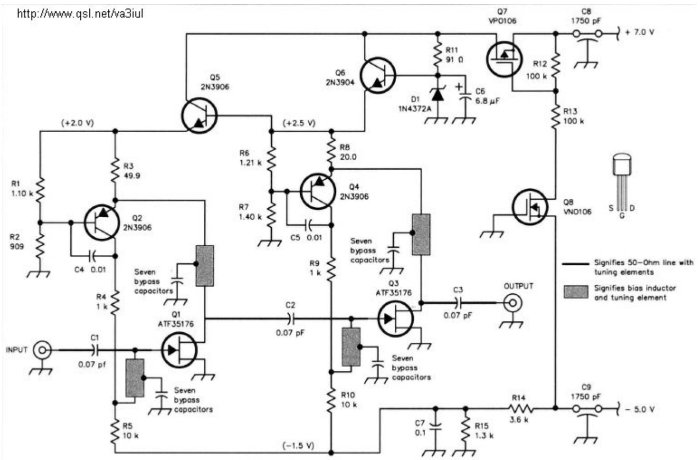
NPT2020 45 W 48 V
DC–2.5 GHz HEMT
$151.29 Digikey NZ





High Electron Mobility Transistor - HEMT

- Depletion mode FET
- Must sequence bias
- Gallium Nitride GaN
- Available, f > 6 GHz
- Power up to 350 W
- Benign impedance
- Currently 2~3 $/Watt



Bias Sequencing

Turning the device ON

1. Set V_{GS} to the pinch-off (V_P), typically -5 V.
2. Turn on V_{DS} to nominal voltage (48 V).
3. Increase V_{GS} until the I_{DS} current is reached.
4. Apply RF power to desired level.

Turning the device OFF

1. Turn the RF power off.
2. Decrease V_{GS} down to V_P.
3. Decrease V_{DS} down to 0 V.
4. Turn off V_{GS}.

Load-Pull Performance: V_{DS} = 48 V, I_{DQ} = 350 mA, T_C = 25°C

Reference Plane at Device Leads, CW Drain Efficiency and Output Power Tradeoff Impedance

Frequency (MHz)	Z_S (Ω)	Z_L (Ω)	P_{SAT} (W)	G_{SS} (dB)	Drain Efficiency @ P_{SAT} (%)
900	1.1 + j0.7	7.3 + j5.5	74	24	68
2000	1.4 - j6.1	2.9 + j2.4	65	17	68
2500	1.5 - j7.6	2.3 + j0.6	64	14	65

Bipolar Junction Transistor

BJT

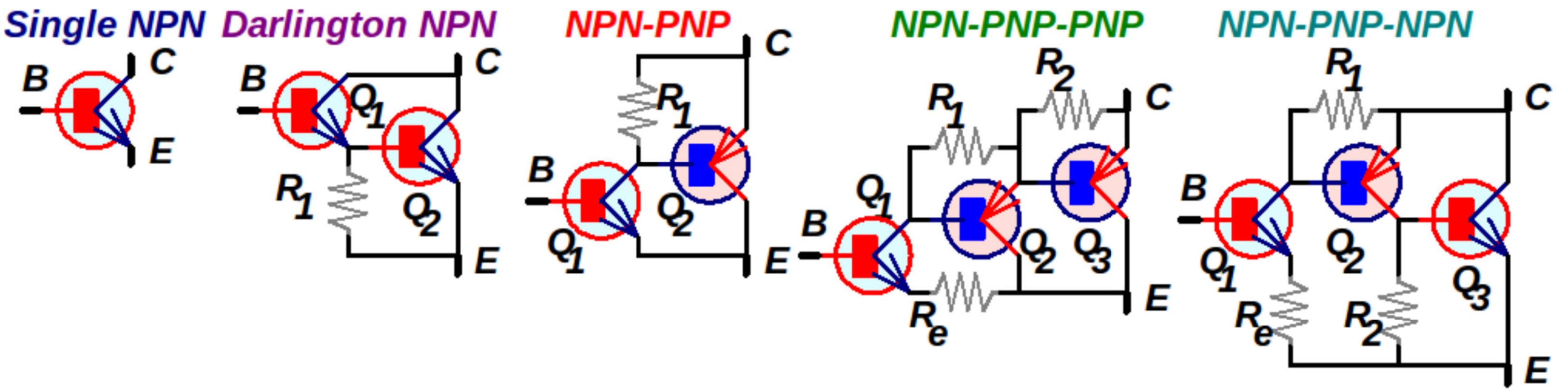
3 Strange and Unusual BJT Circuits – 10 minutes

BJT

Strange and Unusual Transistor Circuits

Composite Bipolar Junction Transistors

- The familiar “Darlington” increases H_{FE}, input 2 x V_{be}
- The NPN-PNP alternative reduces the input V_{be}
- The NPN-PNP-PNP increases H_{FE} but drops 2 x V_{be}
- The NPN-PNP-NPN solves V_{be} and drops only 1 x V_{be}
- Resistors R_1 and R_2 improve turn-off time
- Resistor R_e may be needed to improve stability



Linear concerns on current gain – but can we exploit BJT non-linearity?

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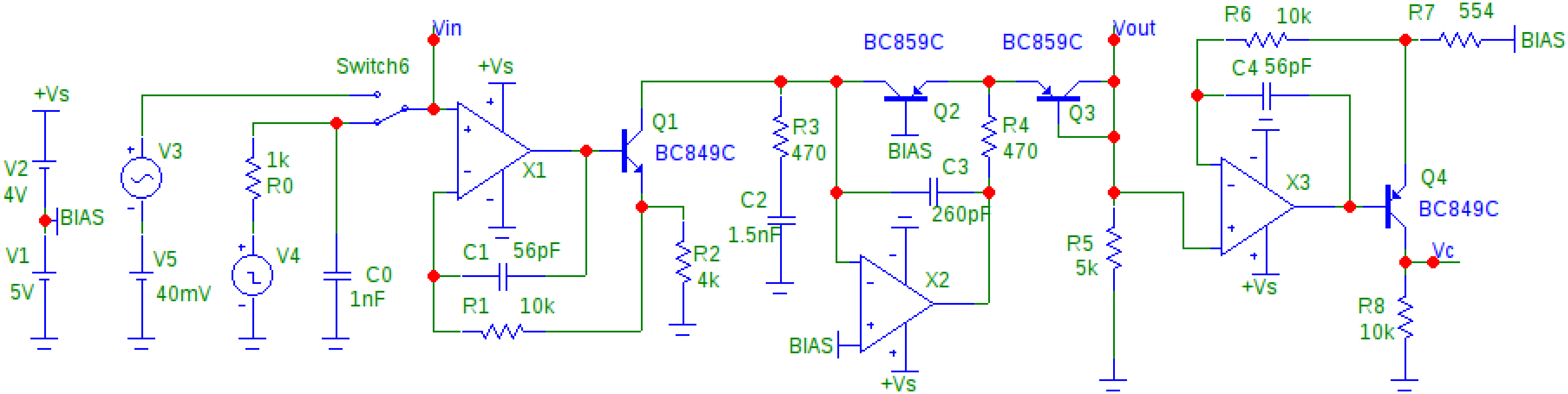
Strange and Unusual Transistor Circuits

Voltage to Logarithm of Voltage (dB) Converter

- Transistor Q2 converts $I_e \sim I_c$ to $\boldsymbol{K} * \mathrm{Log}_e(I_e)$
- Transistor Q3 removes temperature effect of Q2
- OpAmp X1+Q1 - voltage to current conversion
- OpAmp X3+Q4 translate Vout to reference GND



Can we exploit transistor non-linearity to demodulate AM signals?

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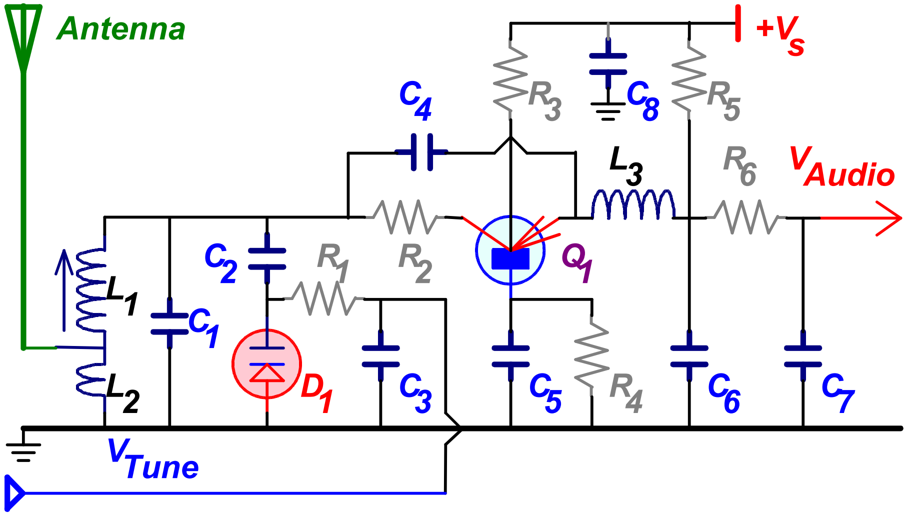
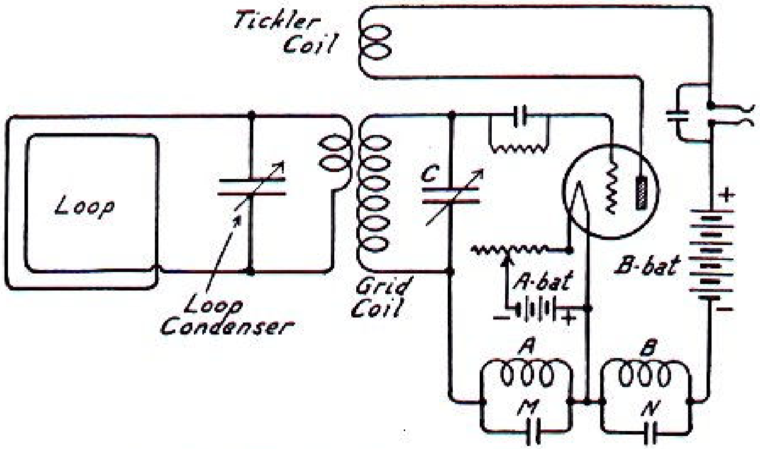
Strange and Unusual Transistor Circuits

Super Regenerative Detector - PNP BJT





Circuits of Super-Regenerative Single Tube Receiver.

- Invented by Edwin Armstrong
- Patented circa 1922 (Wikipedia)
- Used for simple receivers such as door openers
- Oscillations are "quenched" from on to off – RC time constant R5, C6 determines f
- Sensitivity can reach 0.5 µV

Let's see Edwin demonstrate his work!

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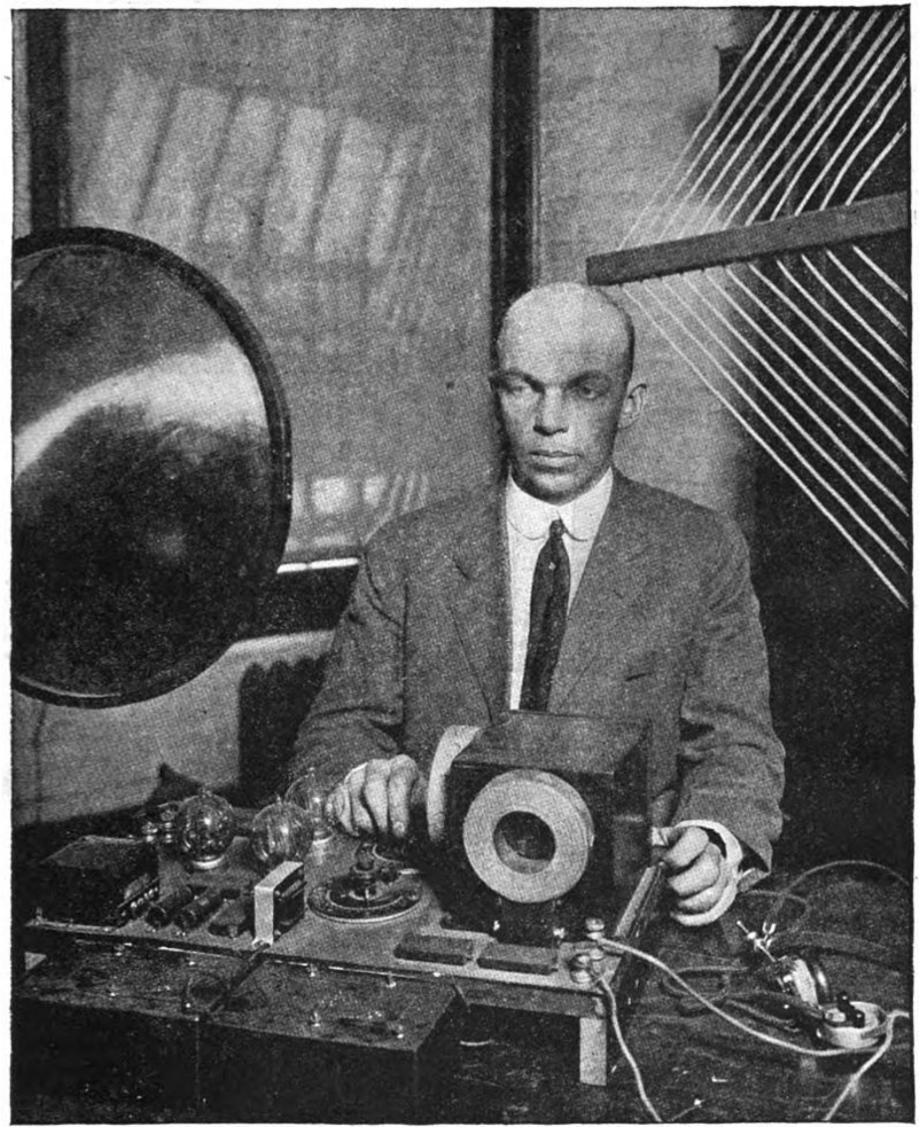
Strange and Unusual Transistor Circuits



- Edwin Armstrong June 28, 1922
- Born December 18, 1890
- Shown demonstrating his 3 tube super regenerative design
- Also invented regenerative Receiver, patented circa 1914
- Also invented the superhet, patented circa 1918
- Held 42 patents
- Patent stolen by Lucian Leve
- Died from suicide, January 1954

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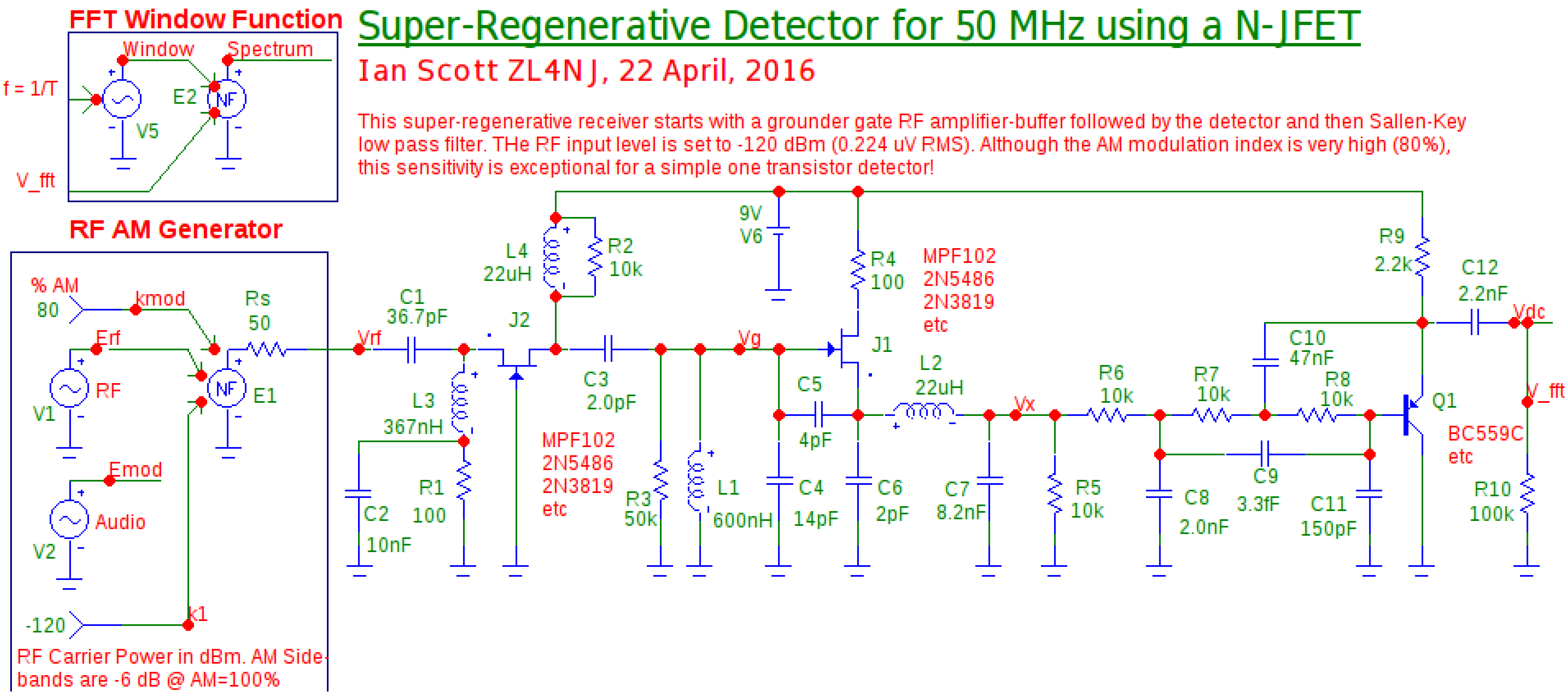
Strange and Unusual Transistor Circuits



This sub circuit generates AM at 50 Mhz, -120 dBm @ 80% modulation

JFET RF amplifier buffer, grounded gate isolation

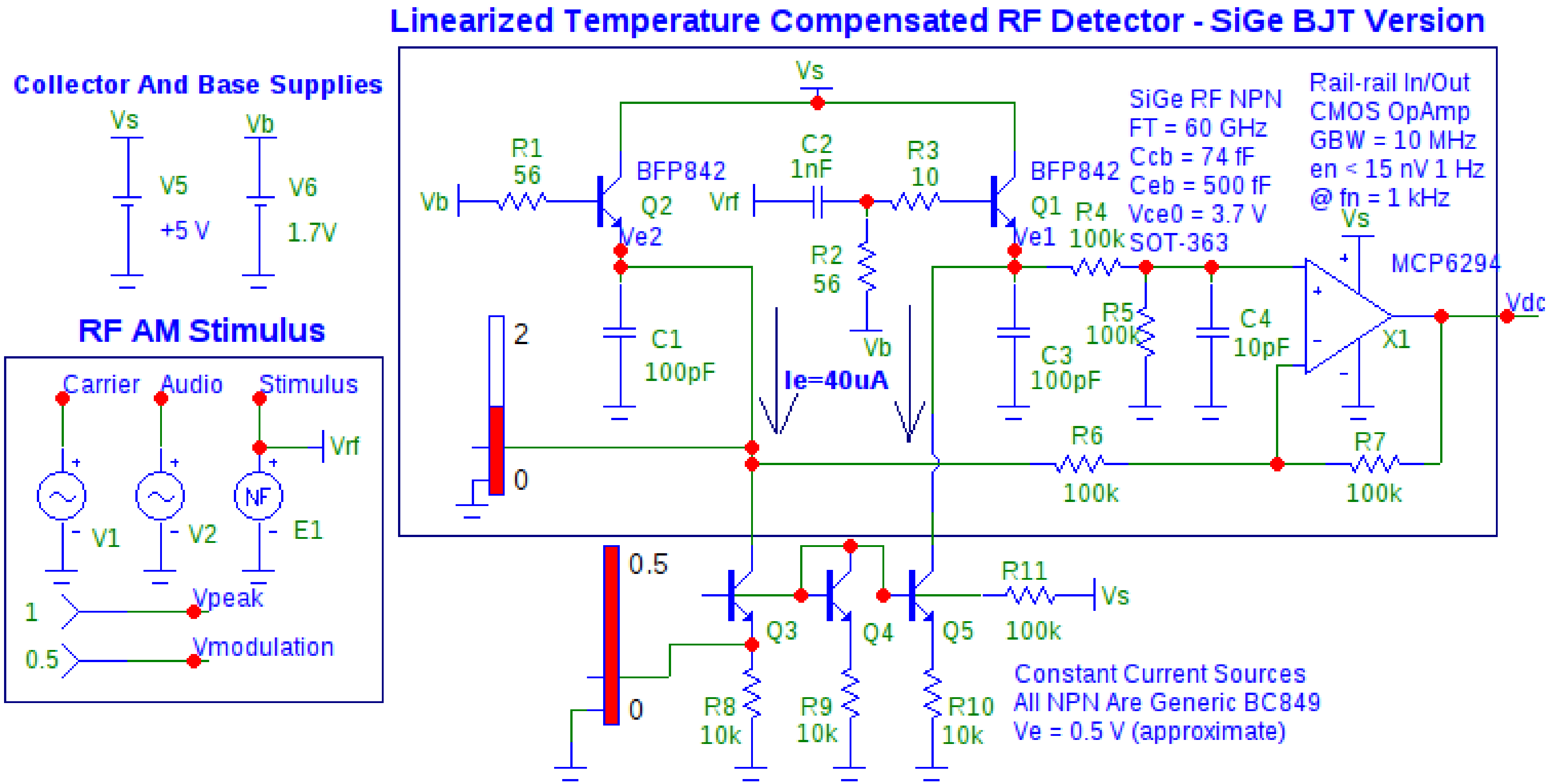
Super-regenerative detector using JFET in simple Collpts. C7, R5 set F_{quench}

Sallen-Key third order low pass filter – removes quench frequency. F_{quench} ~ 35 kHz

Perhaps a modern day 3-transistor version would look like this?

BJT

Strange and Unusual Transistor Circuits

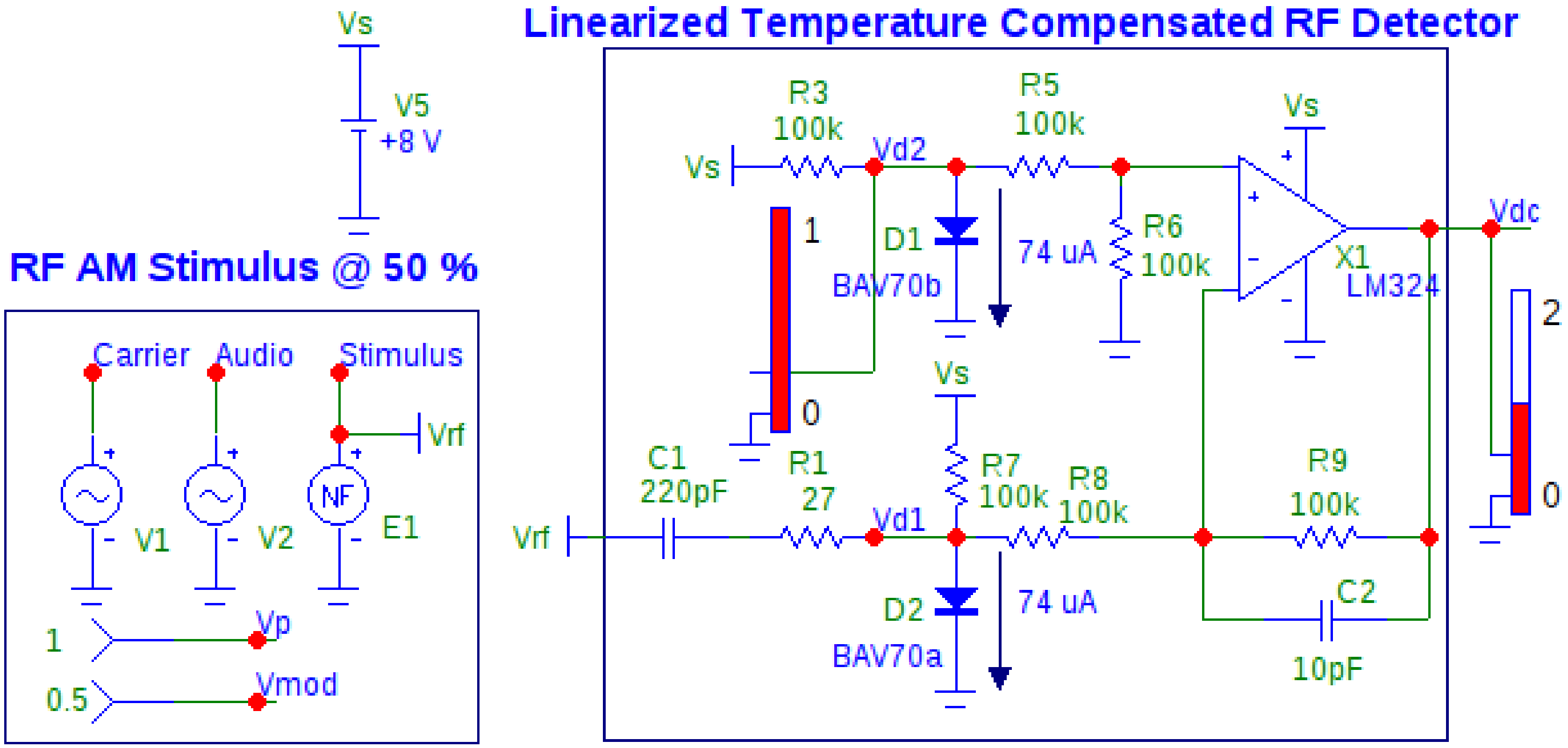


- Ultra-linear thermally compensated active buffer RF detector using two SiGe BJT
- BFP842 FT ~ 70GHz. Simulation at 2GHz. Detection sensitivity down to -50dBm
- Upper frequency range TBD. Maximum input power limited by supply Vs,~+13dBm

A close relative to the “crystal set” radio – its precursor was

BJT

Strange and Unusual Transistor Circuits



- Ultra-linear thermally compensated passive buffered RF detector using two diodes
- Simulation at 500MHz. Detection sensitivity down to -50dBm. **Note** R1 - linearity
- Upper frequency range TBD. Maximum input power up to 10 Watts (+40dBm) / 50Ω

That's some RF detection – how about amplification?

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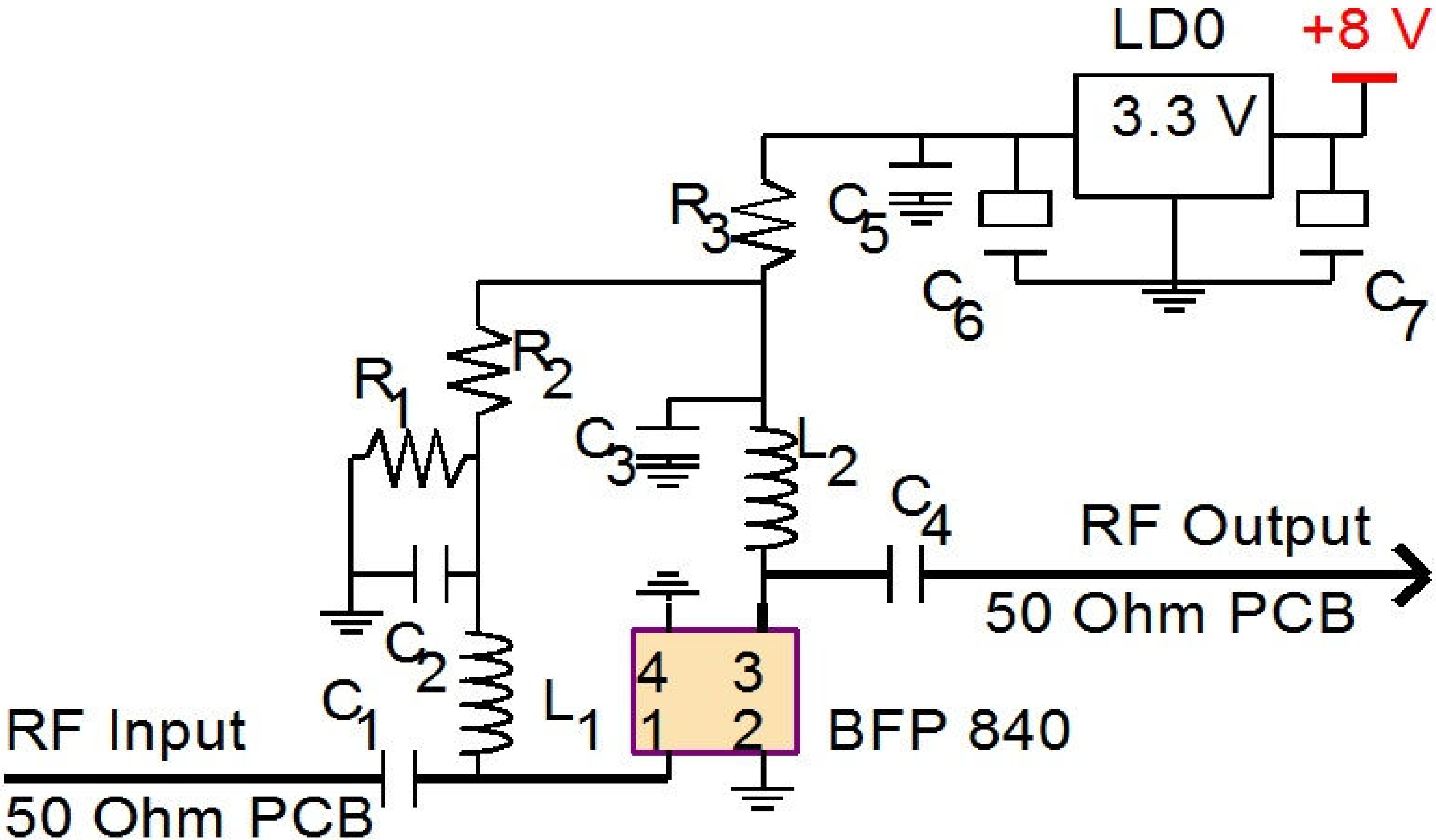
Strange and Unusual Transistor Circuits



LNA Using 70 Ghz SiGe BJT. These don’t need impedance matching for excelent noise figure, e.g. NF < 1 dB at F = 8GHz. Note – most microwave LNA devices use low voltage

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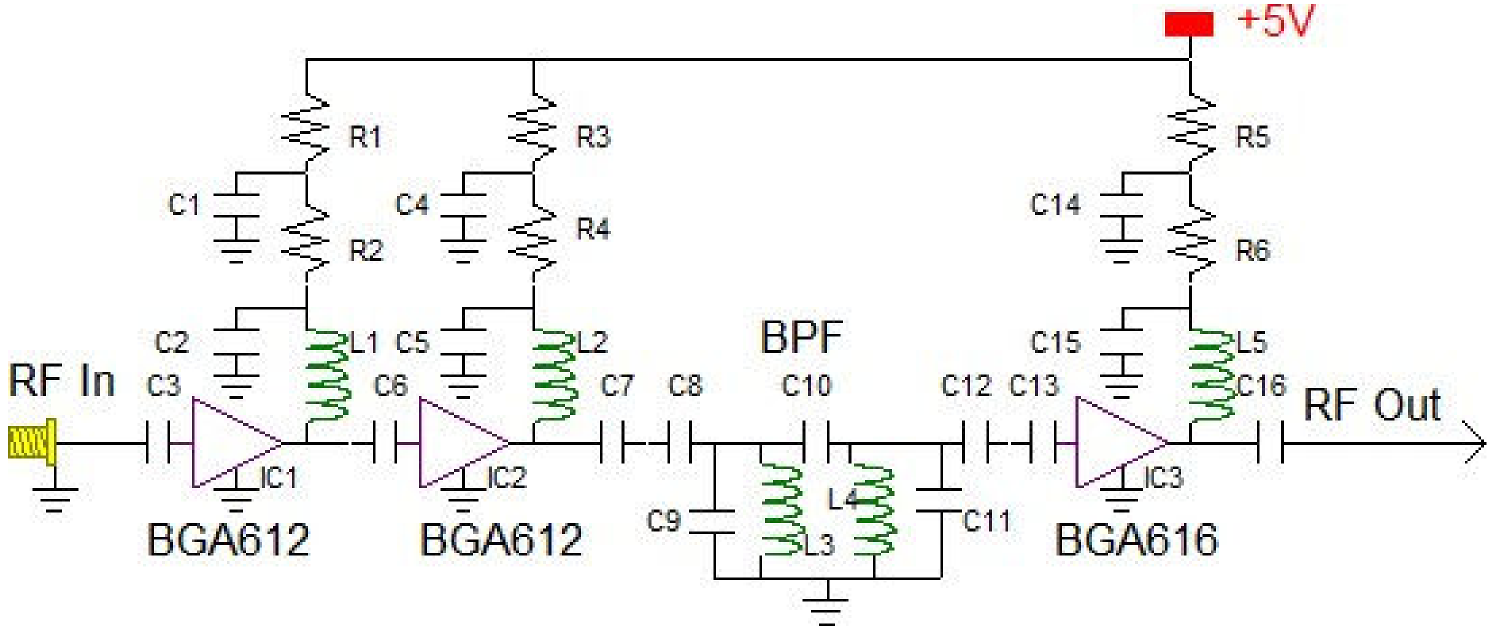
Strange and Unusual Transistor Circuits



- 3 Stage cascaded HF - UHF amplifier, NF ~ 2 dB
- Uses SiGe broadband “MMIC” devices, 17 dB gain
- These use simple BJT “Darlington” configuration

OK – this is only weak signal amplification so far – but where is the RF power?

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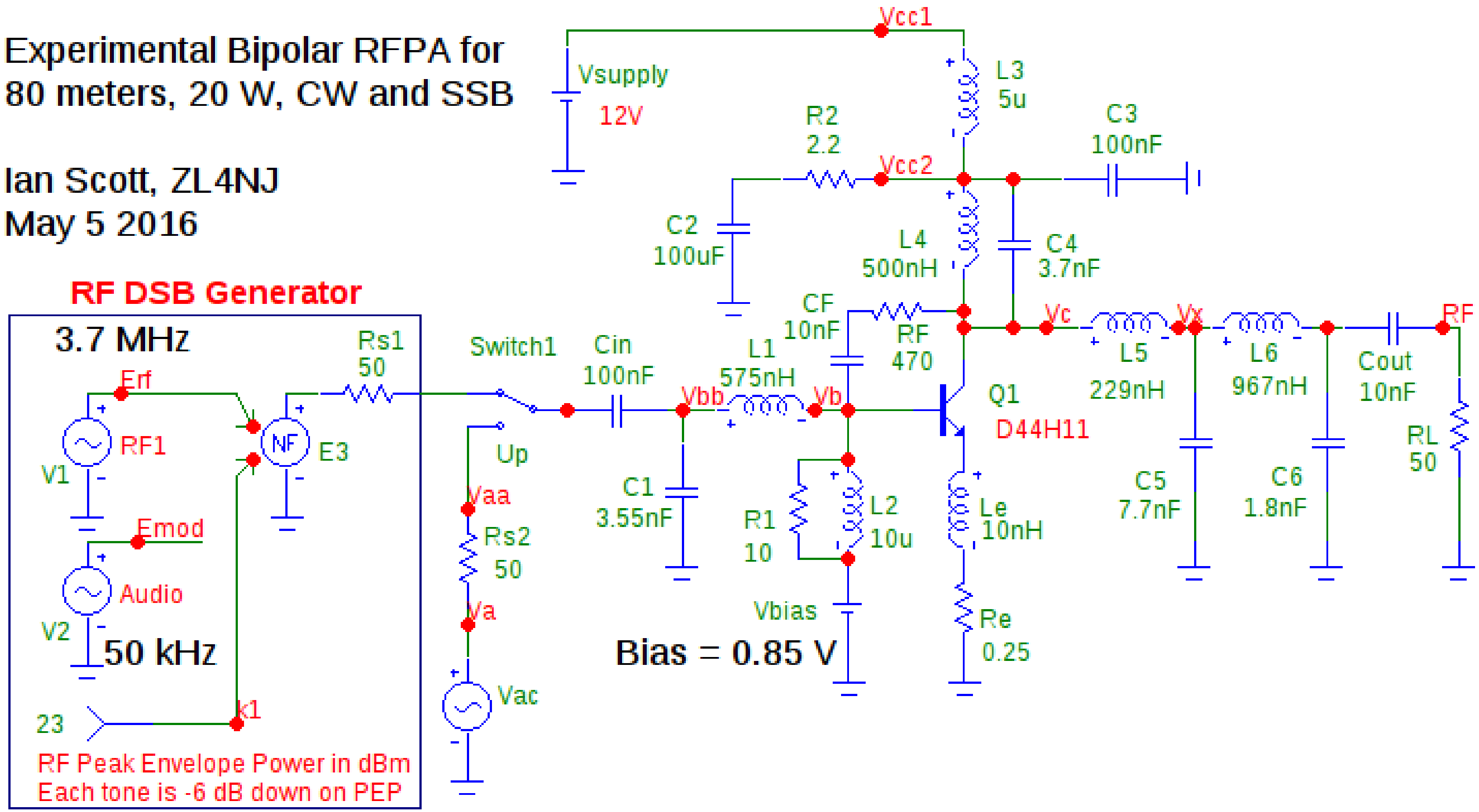
Strange and Unusual Transistor Circuits



Single ended linear RFPA for SSB on 80 meters. This uses a D44H11 “switching” BJT (60 V, 10 Amp, FT = 60MHz in sandard TO-220 case).

This RFPA is drawn in Microcap 11 – could it be simulated with this 2-tone stimulus?

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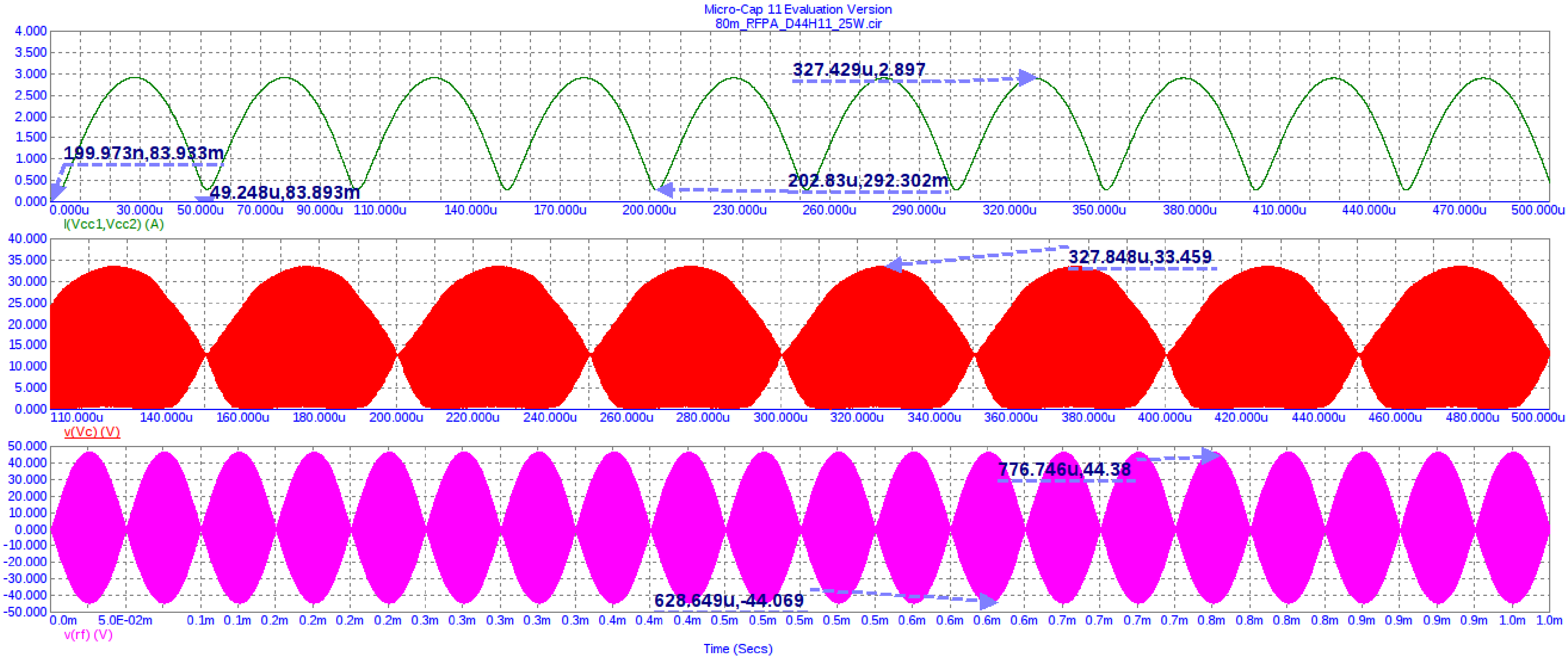
Strange and Unusual Transistor Circuits



Top waveform – supply current variation with RF envelope
Middle waveform – collector voltage – note heavy saturation!
Lower waveform – envelope is now smooth and symmetrical due to N=4 low pass output matching network, V_{peak} ~ 43 Volts → PEP = $43^2 / (2 \times 50)$ = 18.5 Watts

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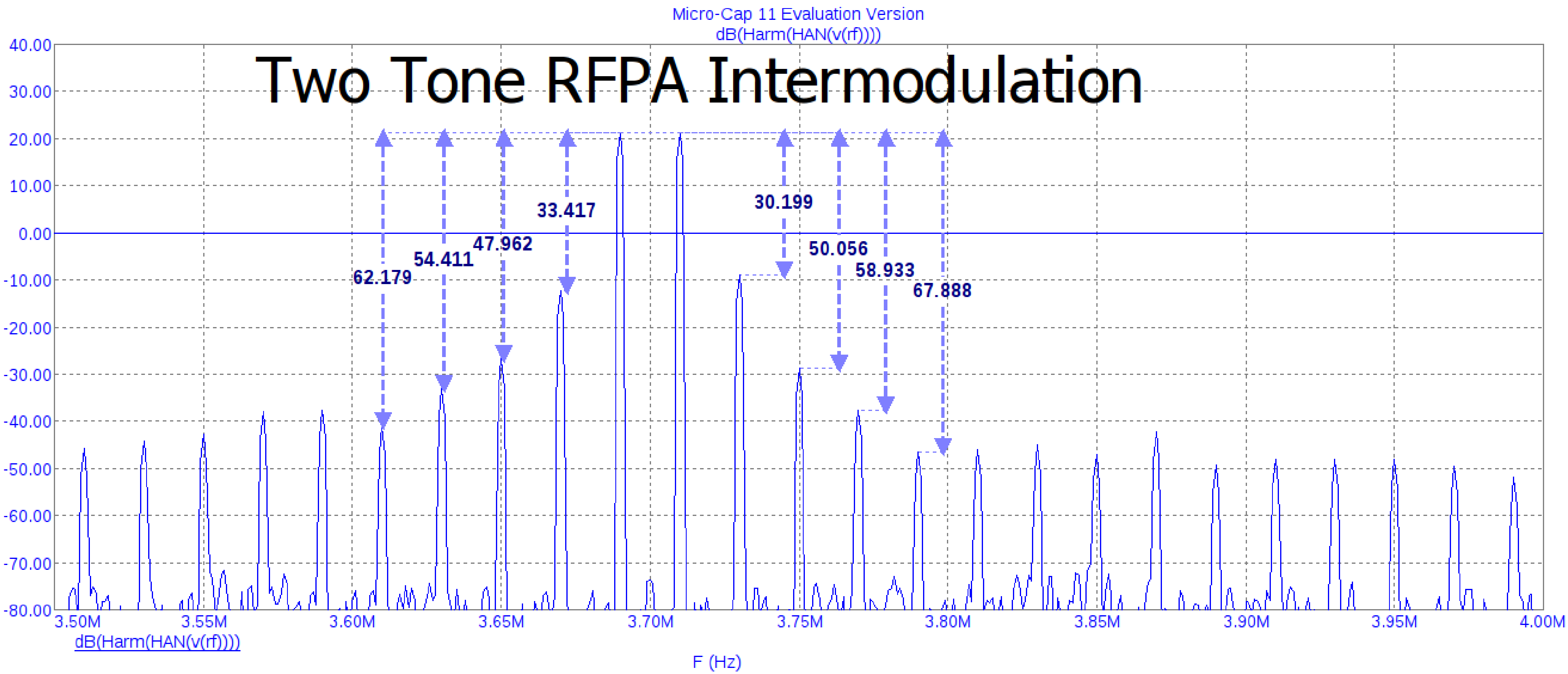
Strange and Unusual Transistor Circuits



Fast Fourier Transform (FFT) spectrum from time domain data

But can you believe it? Or even does this question even make sense?

BJT

Strange and Unusual Transistor Circuits

Aside – Why use computer simulation?

- **Provides a "sneak preview" for circuit or system behaviour**
- **Weeds out designs that would perform poorly**
- **Educational tool – illuminates circuit behavior**
- **Many simulation tools are free for educational use**
- **Expensive test equipment is avoided**

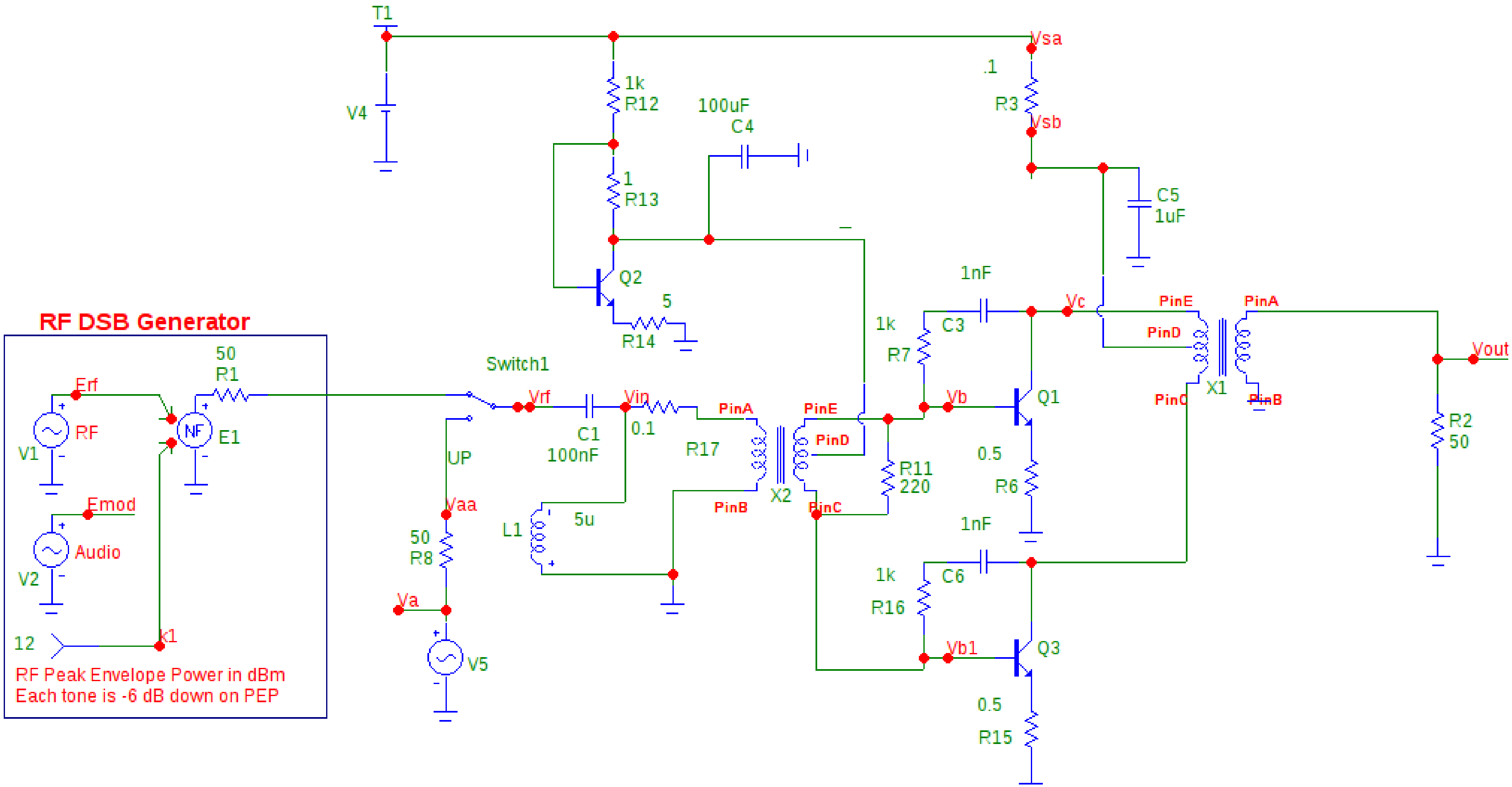
Note – successful simulation results do not guarantee successful physical outcomes but poor simulation results guarantee poor physical results!

Note also, Agilent' "ADS simulation suite" costs a couple of million $

Companies don't waste money on items that don't return!

BJT

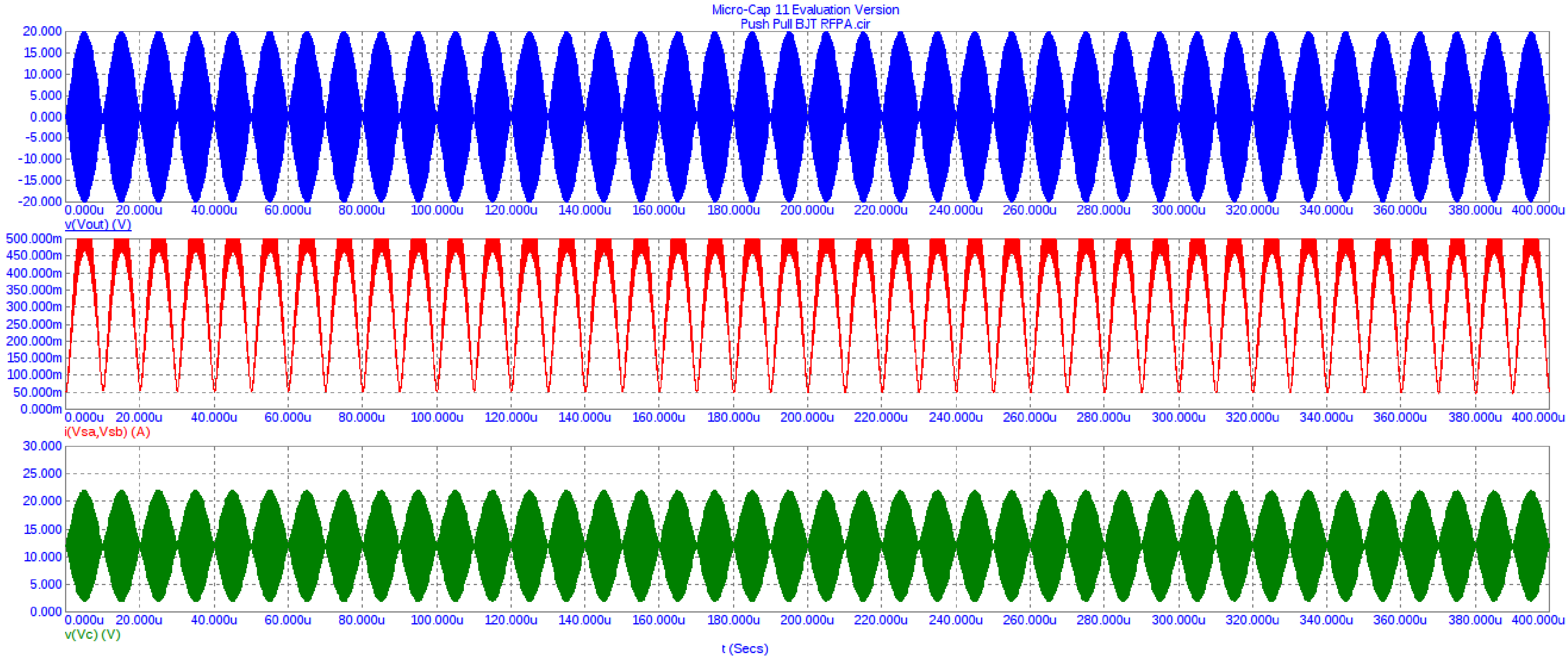
Strange and Unusual Transistor Circuits



Push-pull transformer coupled BJT RFPA, biased for class AB (Q2) – this provides thermal feedback to stabilize operating point. Now let's see the time domain plots

BJT

Strange and Unusual Transistor Circuits



Top plot – RF output voltage waveform, 20 V_{peak} → PEP = 20^2 / (2 x 50) = 4.0 Watts
Middle plot – supply current variation with 2-tone envelope
Lower plot – Voltage waveform at collector – note symmetry, forced by output center-tapped transformer

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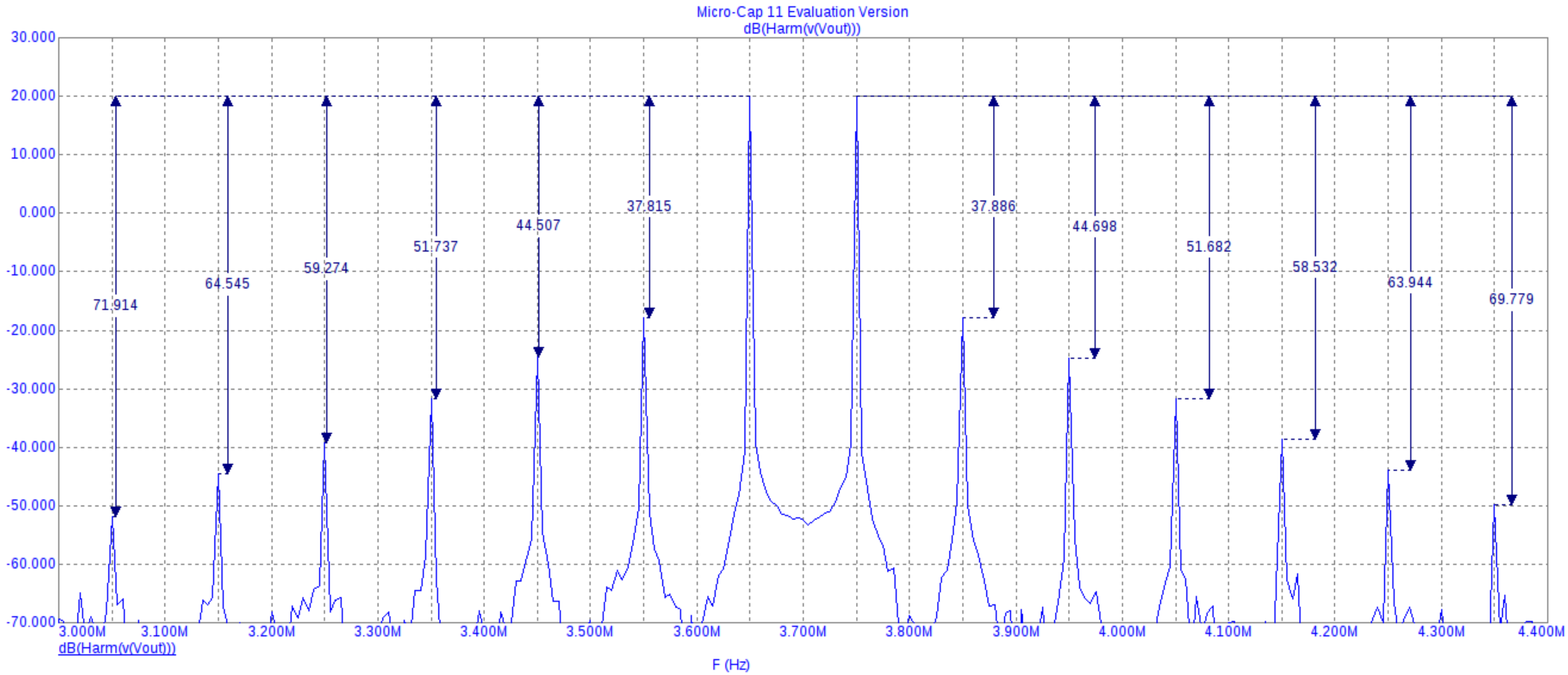
Strange and Unusual Transistor Circuits

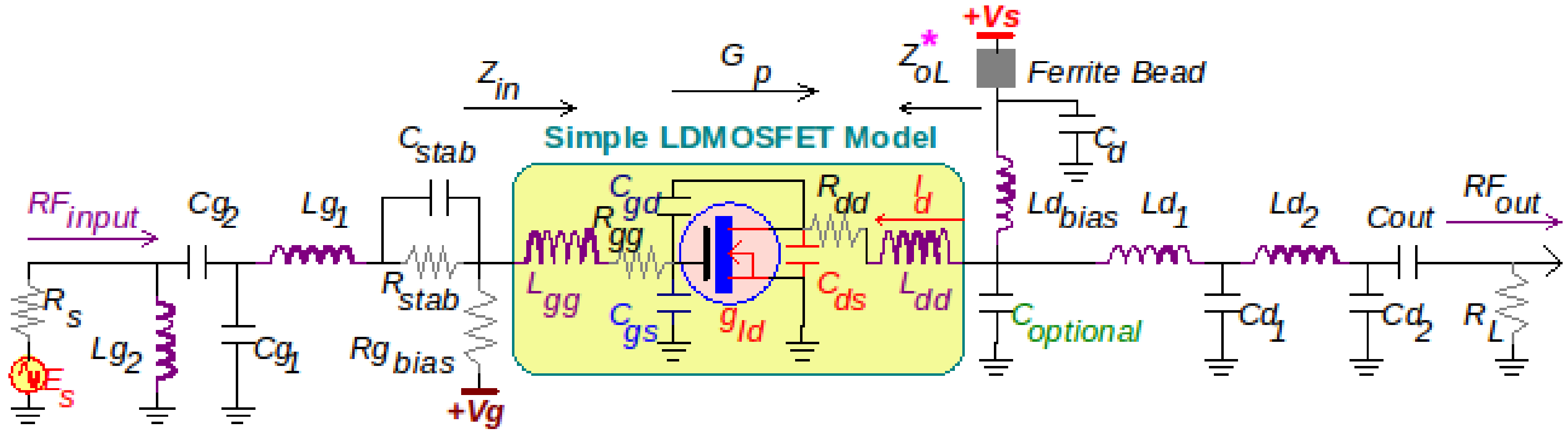


Output spectrum using FFT

RF BJT are the persona-non-grate in RFPA design circles these days. The new kids on the block are LDMOS devices!

BJT

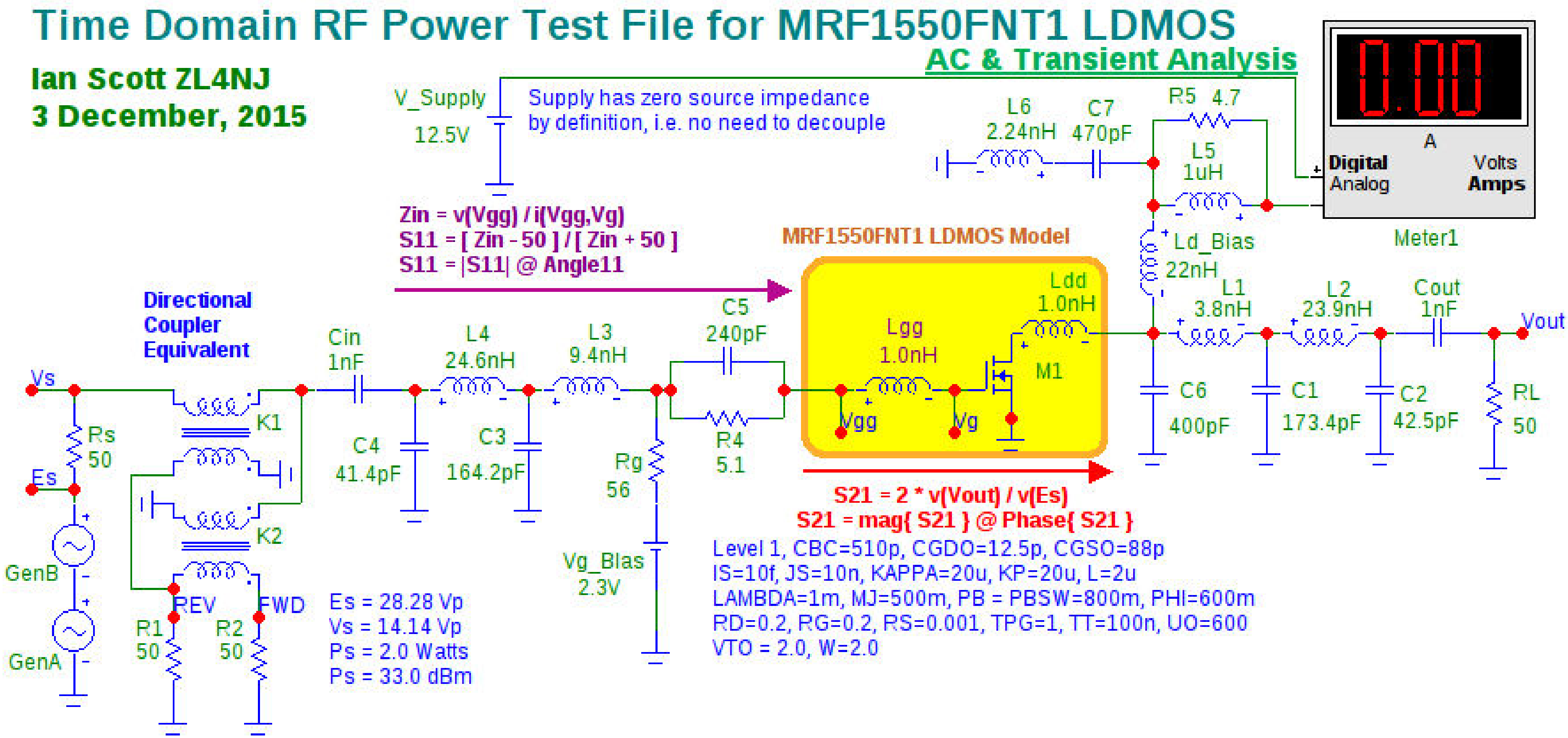
Strange and Unusual Transistor Circuits



- Simple LDMOS RF Power Amplifier
- High-pass, low pass input matching network
- Series R-C gate stability network (essential)
- Two section “Mathhaei” output match

BJT

Strange and Unusual Transistor Circuits



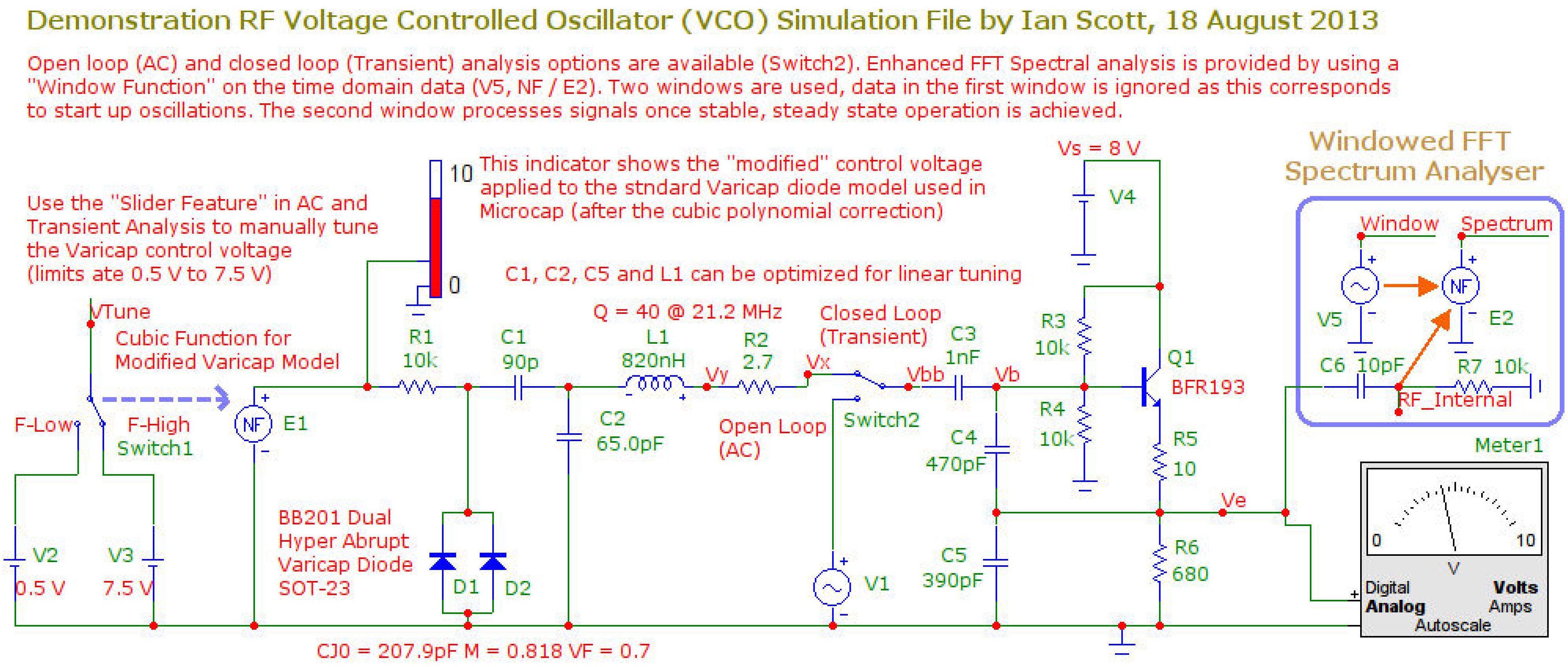
50 Watt VHF RF Power Amplifier using MRF1550 LDMOS Device

This topology is typical for all single ended LDMOS RFPA – lumped elements components are replaced with PCB micro-stripline at higher frequency and RF power

That's enough RF power for now – what about oscillators?

BJT

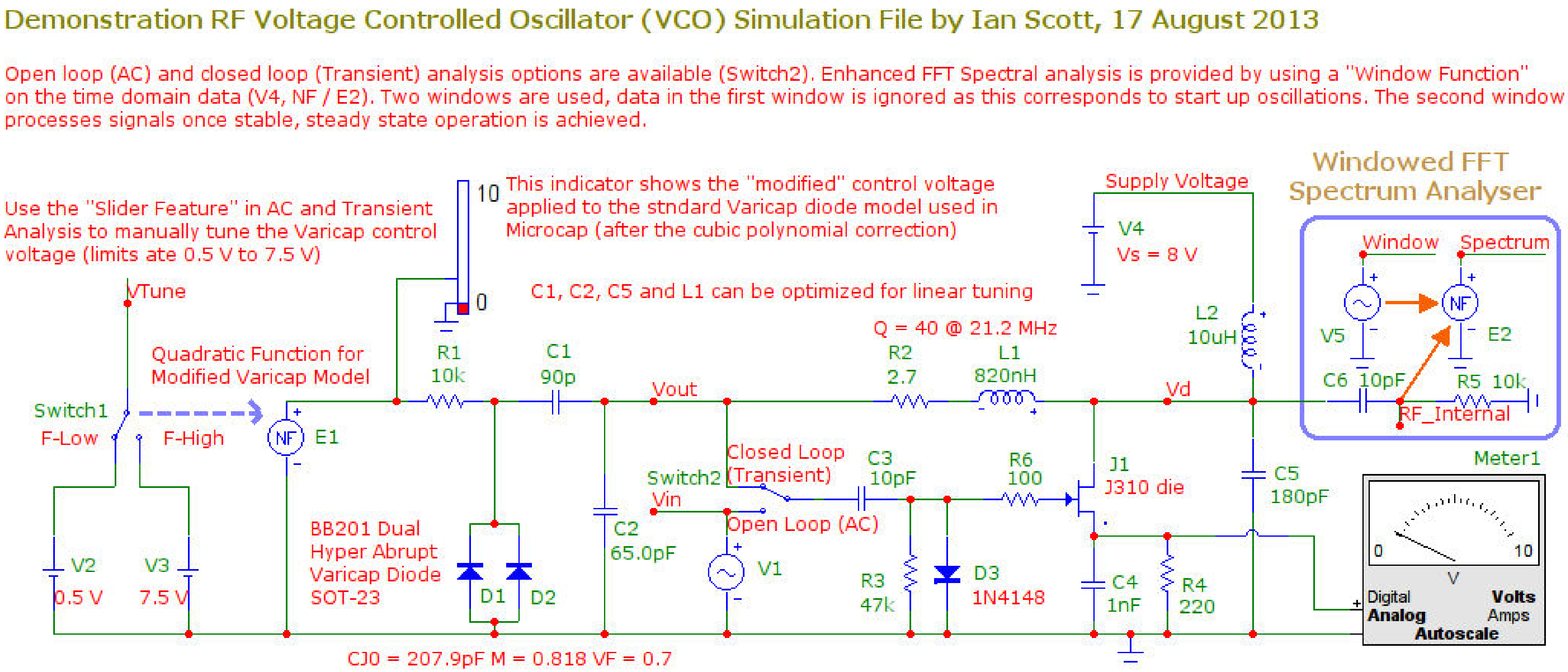
Strange and Unusual Transistor Circuits



Common collector BJT “Colpitts” oscillator (from Edwin H. Colpitts) using a BFR193 “Arsenic implanted interdigitated emitter” NPN. This can be divided by 4 to get 5.5 MHz

BJT

Strange and Unusual Transistor Circuits

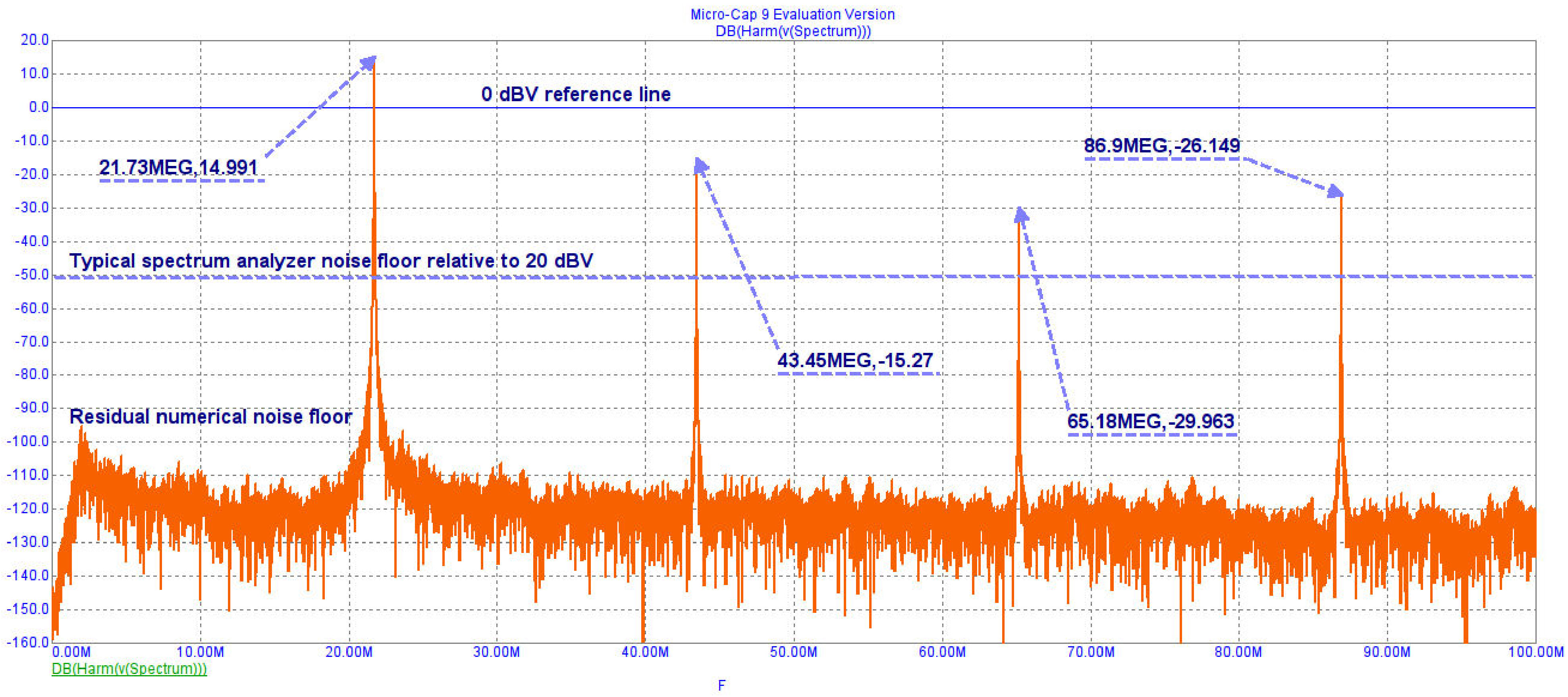


Common source JFET "Colpitts" oscillator using a J310 "generic" device, also centered at 21.2 MHz. All oscillator configurations are "topologically equivalent" and perform the same!

Oscillator devices run in class C and therefore always produce harmonics as we will see...

BJT

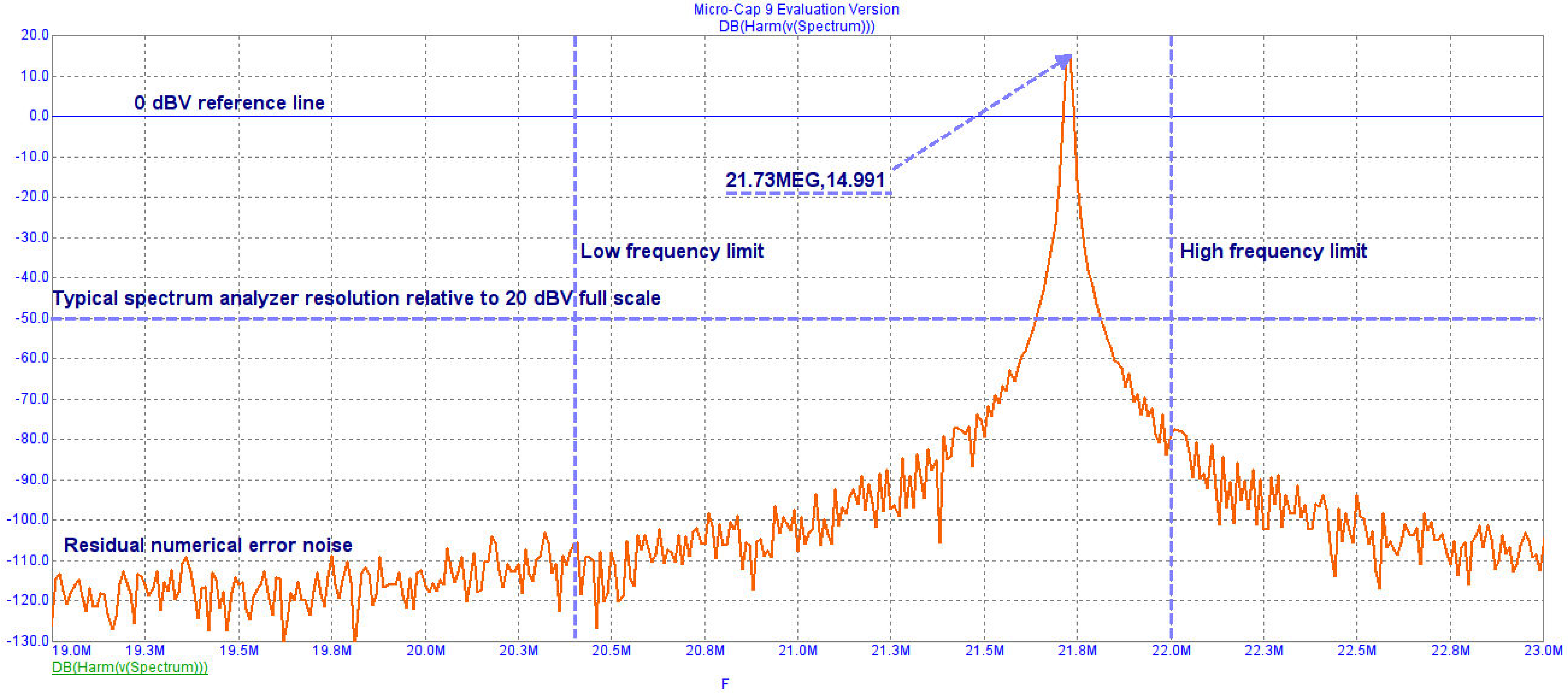
Strange and Unusual Transistor Circuits



This FFT plot shows a succession of harmonics but quite well filtered due to “Q” - but what of the “phase noise”much closer in?

BJT

Strange and Unusual Transistor Circuits

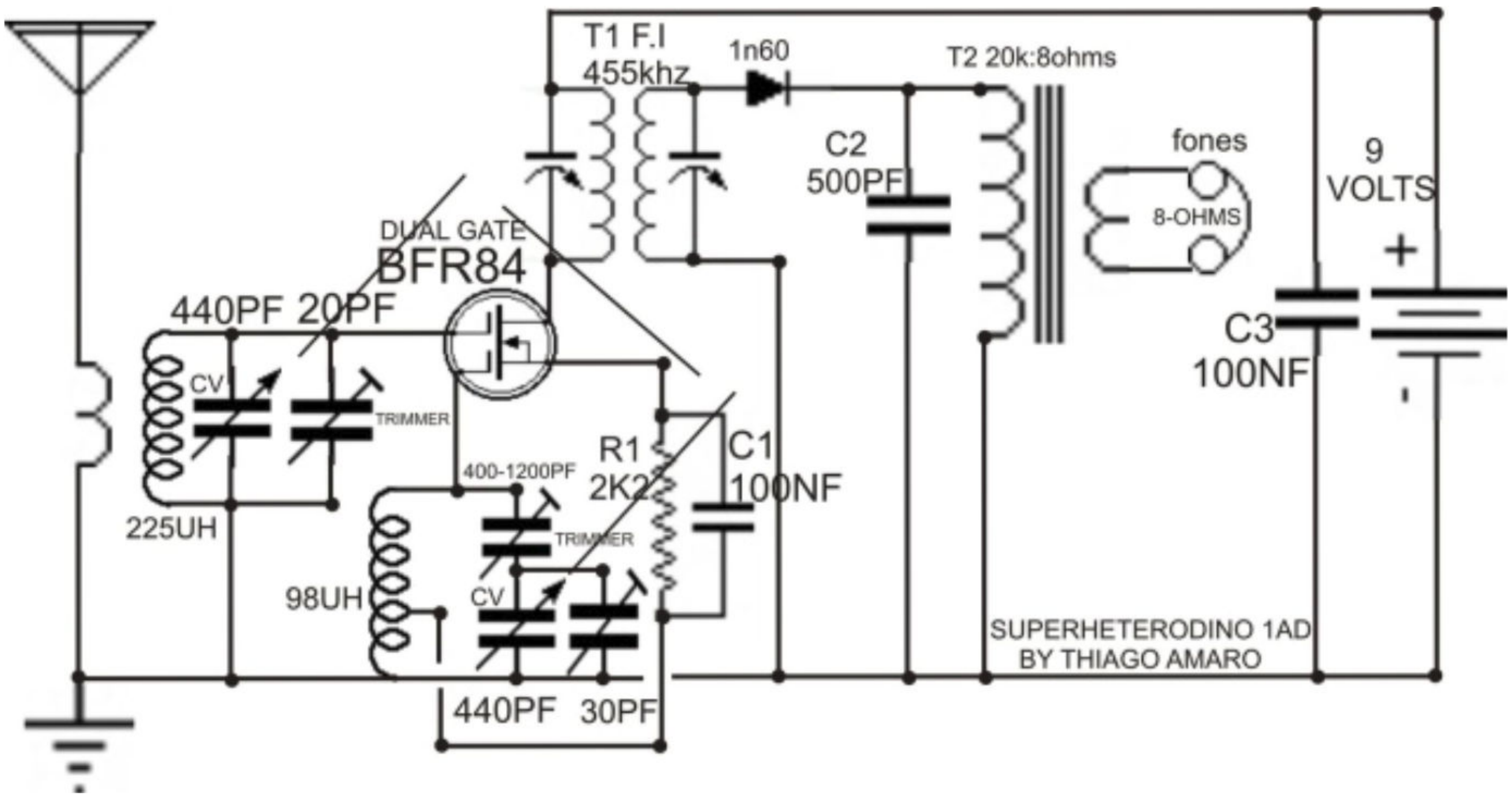


An oscillator can be represented as broad band spectral noise multiplied by a tuned circuit response - “Q multiplied” by positive feedback.

What can an oscillator be used for ?

BJT

Strange and Unusual Transistor Circuits



Single dual gate MOSFET Superhet Receiver – seems like some amateur found a use!

Bipolar Junction Transistor

BJT

Useful Internet Sites

Component Suppliers

http://www.digikey.co.nz/product-search/en
http://nz.mouser.com/Electronic-Components/
http://nz.rs-online.com/web/
http://nz.element14.com/

Useful Free Software Downloads

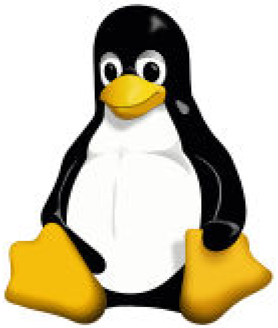
https://www.libreoffice.org/
https://inkscape.org/en/download/
http://www.spectrum-soft.com/demo.shtm
http://www.linear.com/designtools/software/
http://qucs.sourceforge.net/
https://www.expresspcb.com/free-cad-software/
http://www.sillanumsoft.org/download.htm
http://www.basic256.org/index_en
http://www.scilab.org/
https://www.gnu.org/software/octave/

Linux OS

http://www.ubuntu.com/
https://www.linuxmint.com/
https://getfedora.org/
https://www.debian.org/

Virtualization Software

https://www.virtualbox.org/



Bipolar Junction Transistor

BJT

Summary – Topics Covered

- **BJT History – germanium point contact transistor, BJT, migration to silicon, high frequency improvements**
- **BJT dynamic behaviour, current controlled model, h parameters, frequency limitations, noise characteristics**
- **Strange and interesting BJT circuits**

Any Final Questions or Comments?