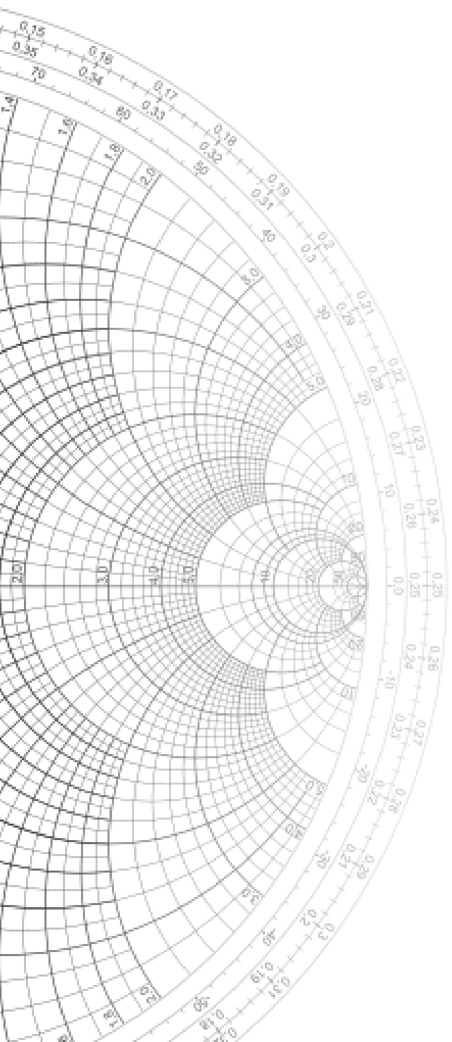
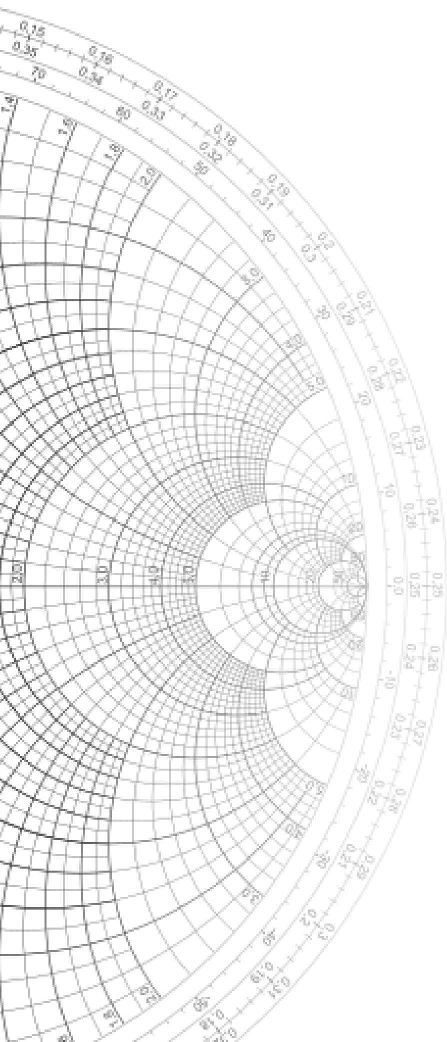
Transistor Load Lines

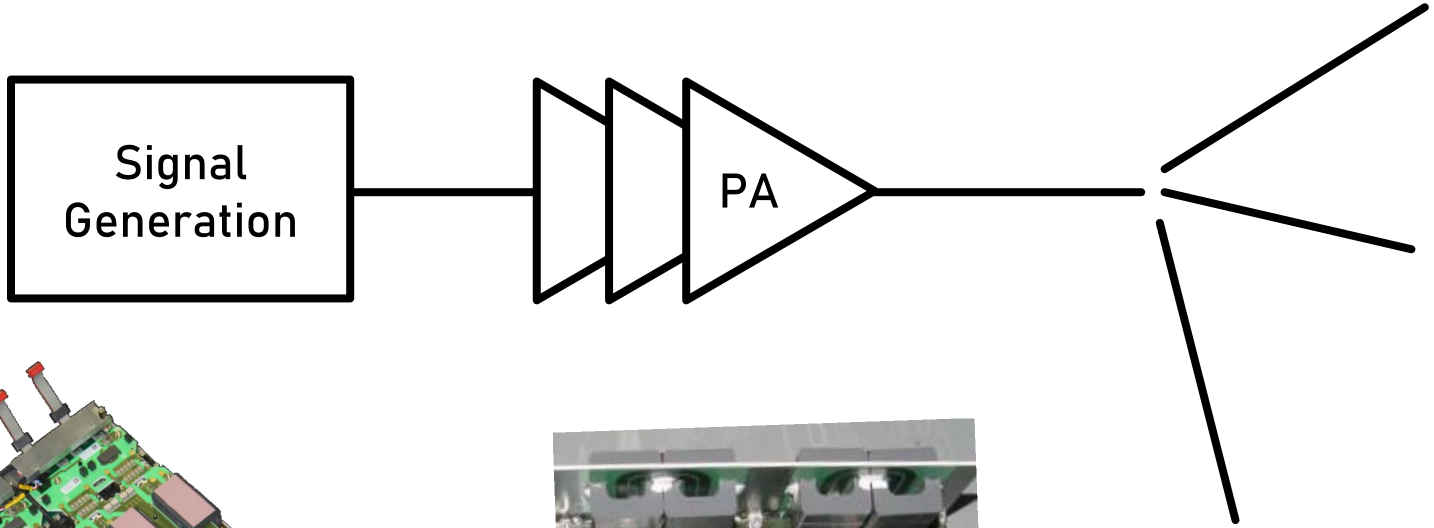
Contents

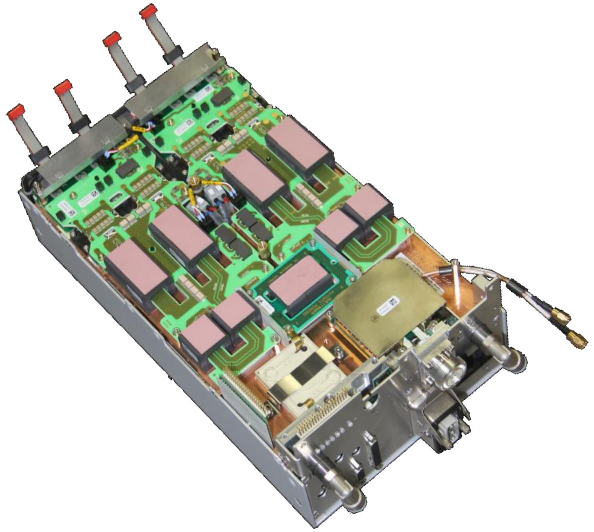


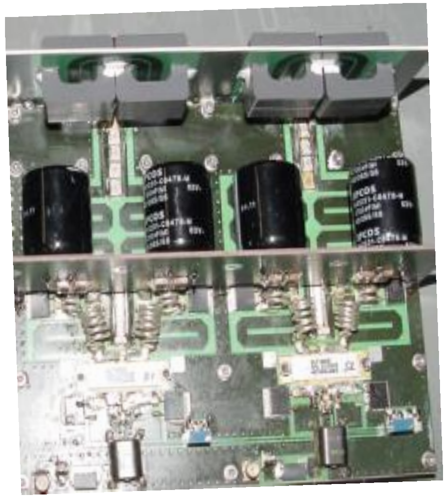
- What are load lines
- Why are they useful
- How to measure them
- PA classes
- Using in PA design
- Advanced
  - Class F
  - Load modulation/supply modulation
  - Rectifiers

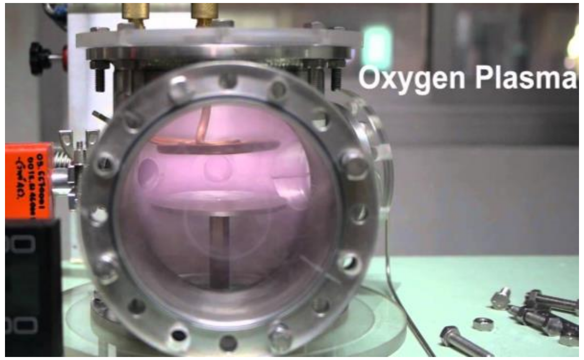
Motivation





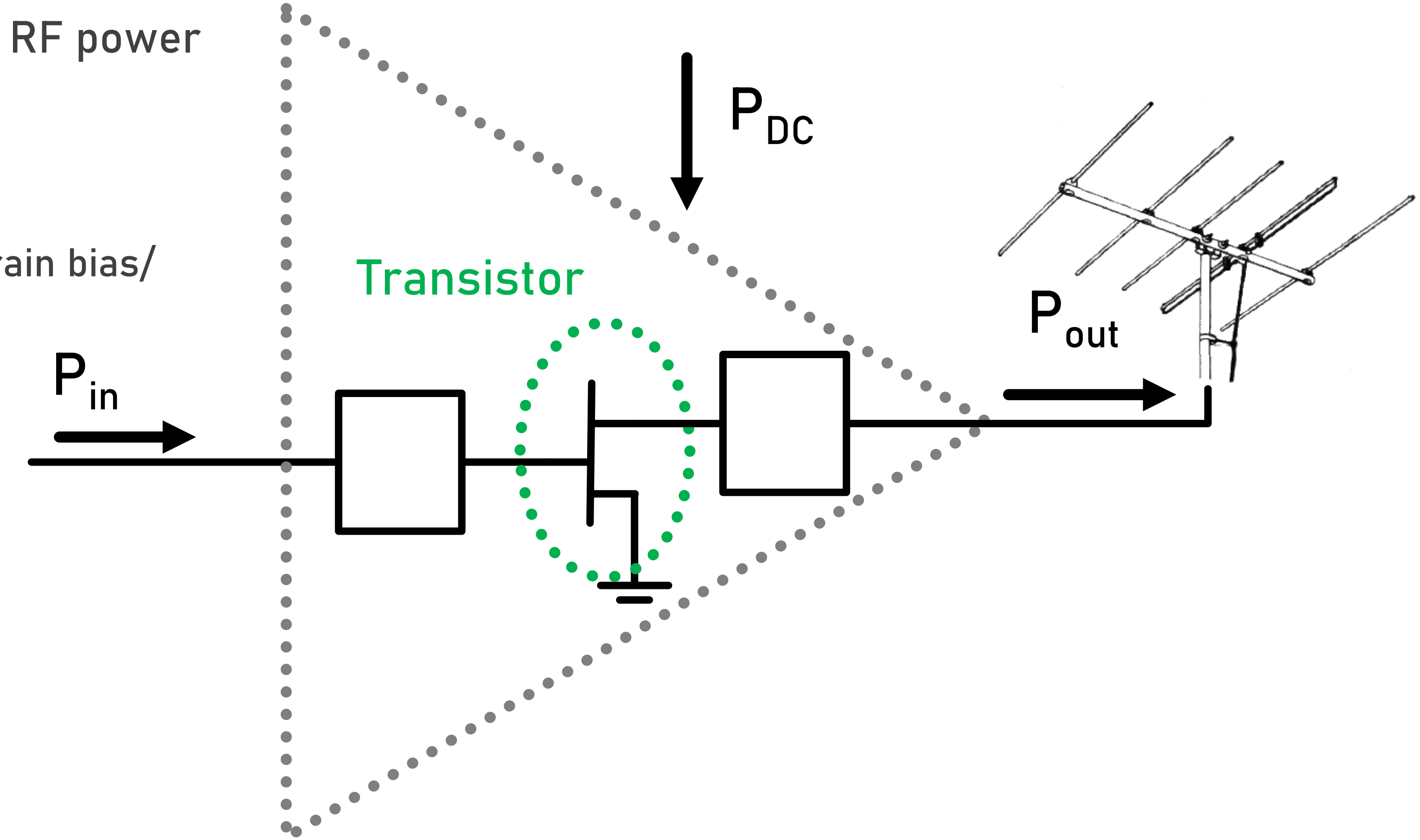




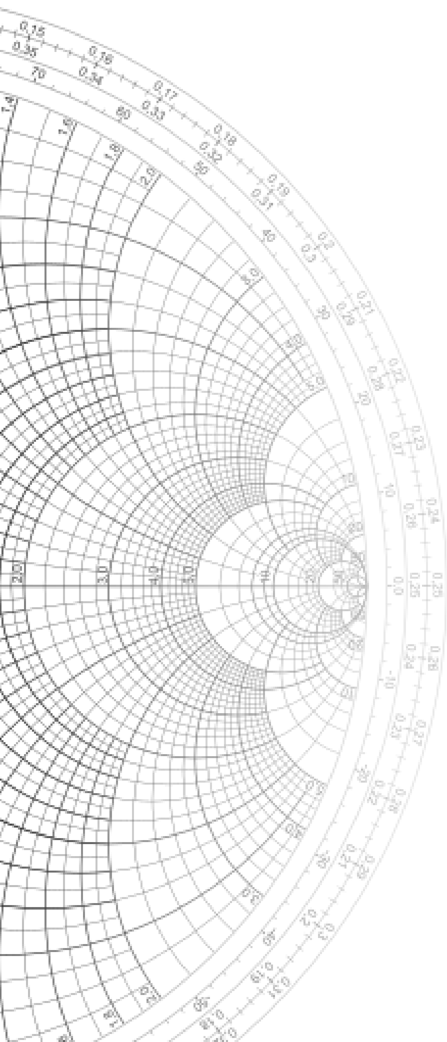


PAs

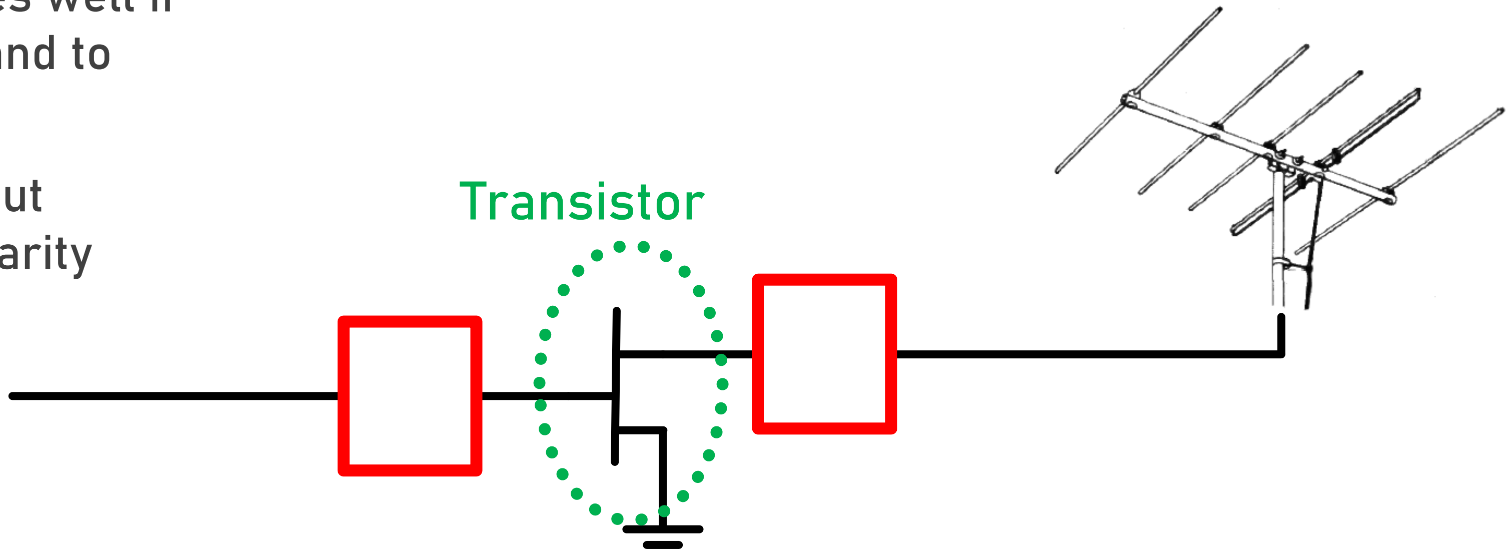
- Amplify RF signal
- Convert DC power to RF power
- Inputs:
  - RF input power
  - DC input power/ Drain bias/ Supply voltage
  - Gate bias
- Outputs:
  - RF output power
  - Heat!



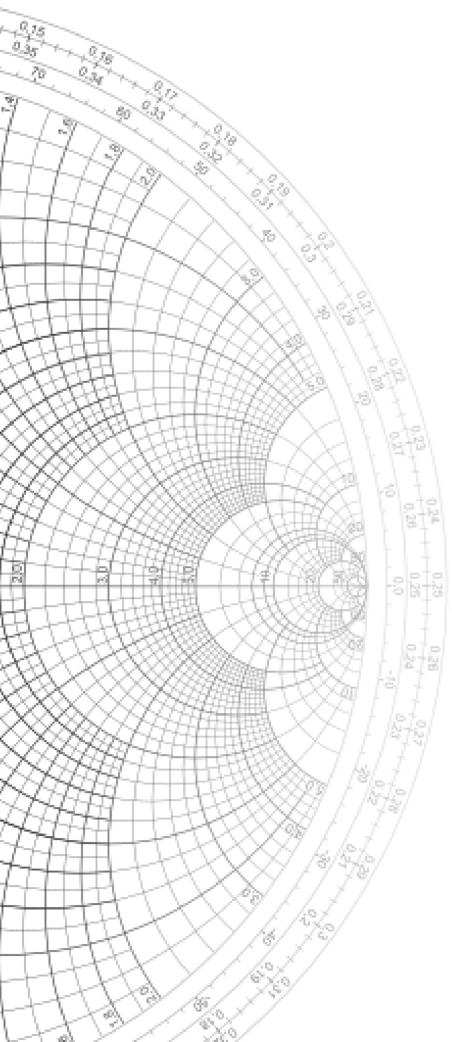
PAs



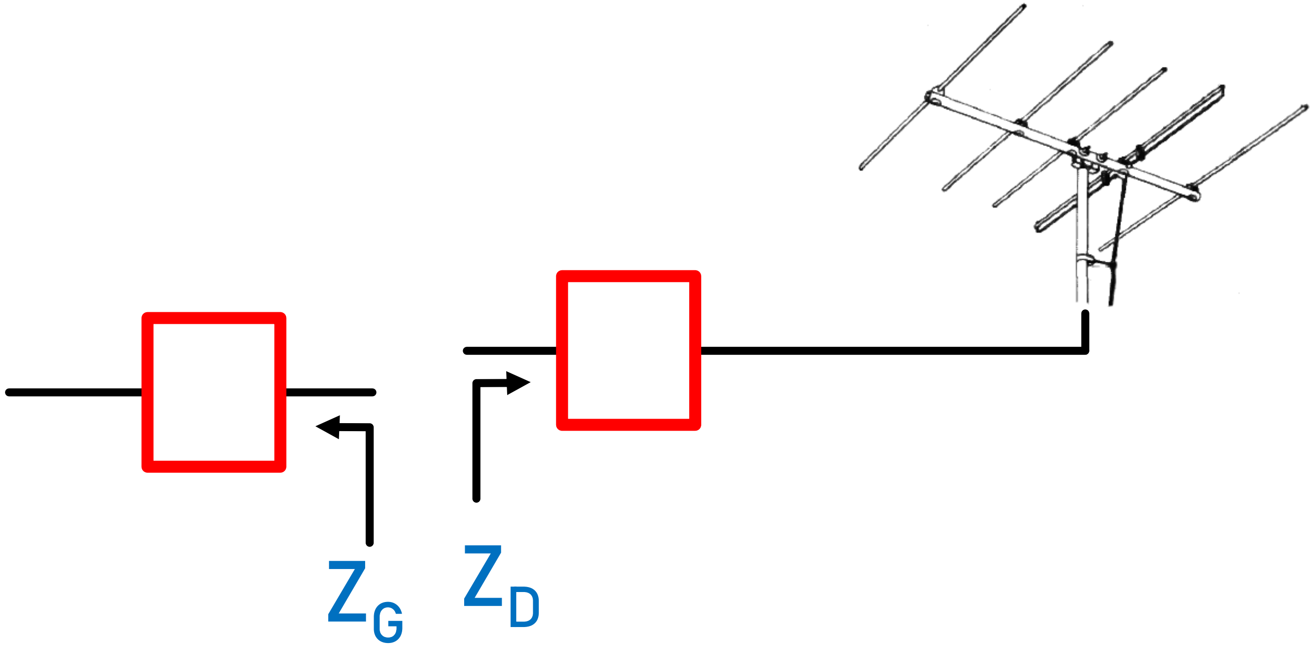
- Important part: Matching Networks
- Make sure PA operates well if connected to source and to load
- Determines gain, output power, efficiency, linearity



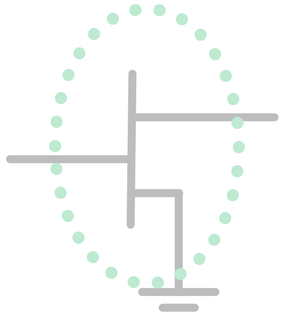
Matching networks



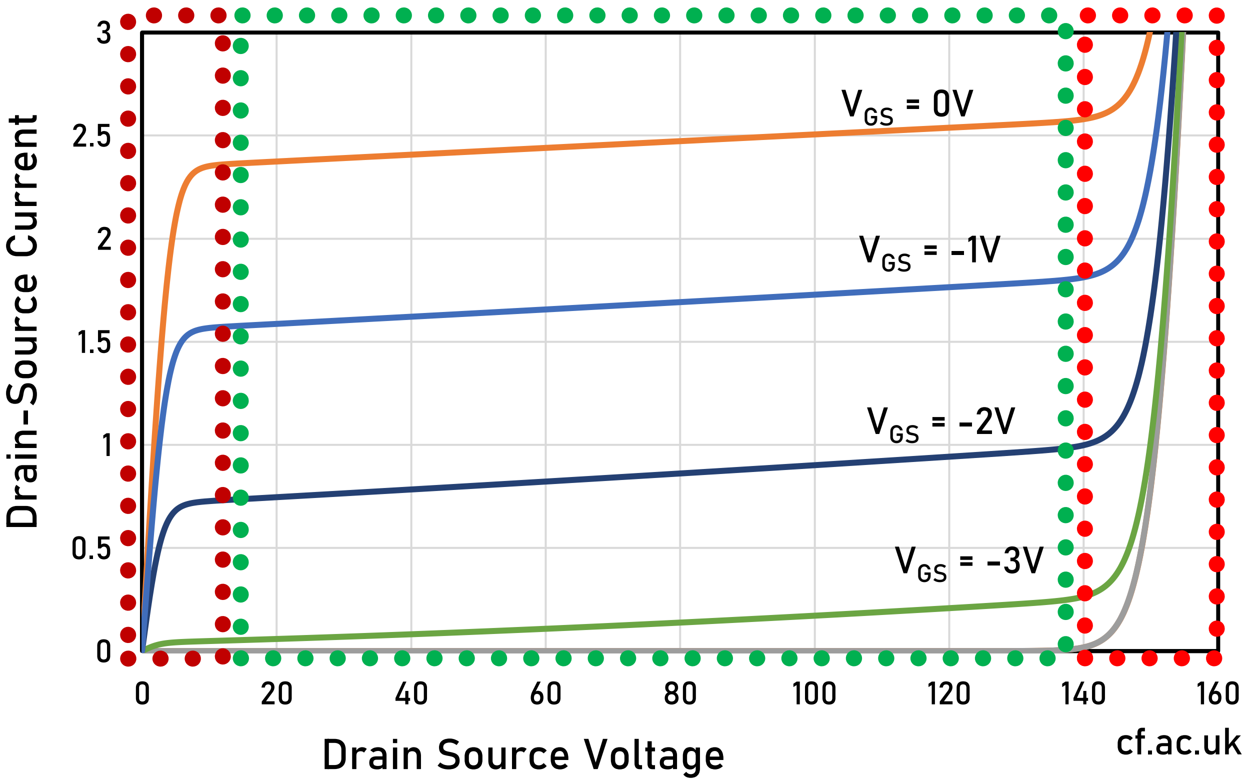
- Need to know impedances
- Might be in data sheet
- Eval board might be available
- If model available and usable, can do load-pull simulation (or ask someone else to do it)
- If no good model, can do load-pull measurement (or ask someone)



IV Curves



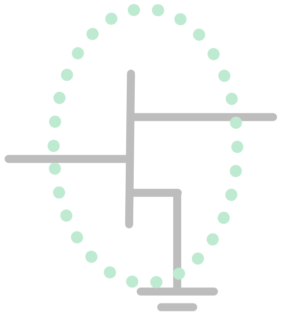
- Take step back and look at transistor
- IV show how current behaves for combinations of gate and drain voltage
- 3 regions
  - **Linear region,** transistor behaves like resistor, funnily enough the transistor isn't very linear here
  - **Saturation region**, current depends mostly on gate voltage
  - **Breakdown region** **Don't be here**

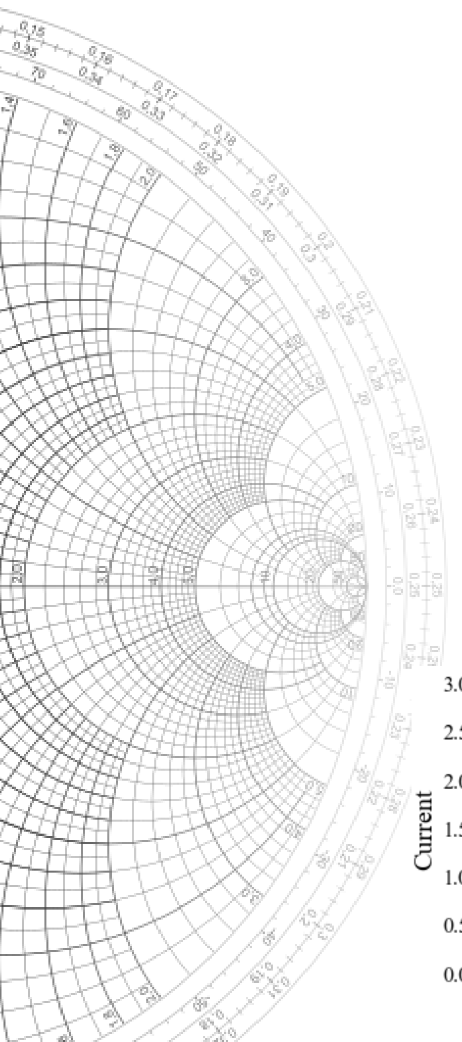


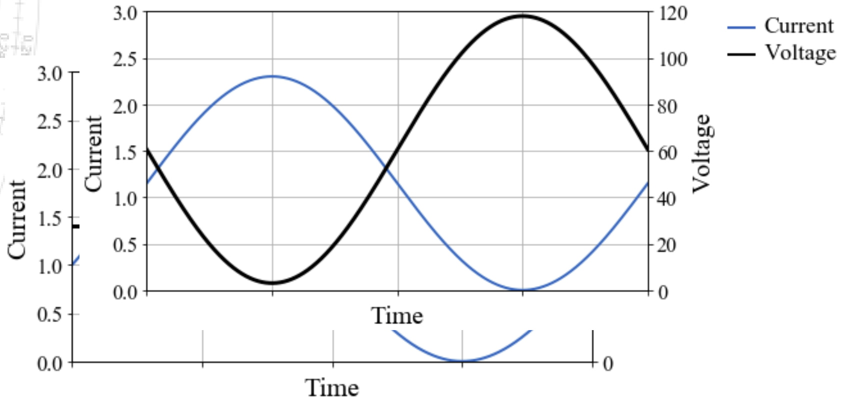
Enter Load-Lines

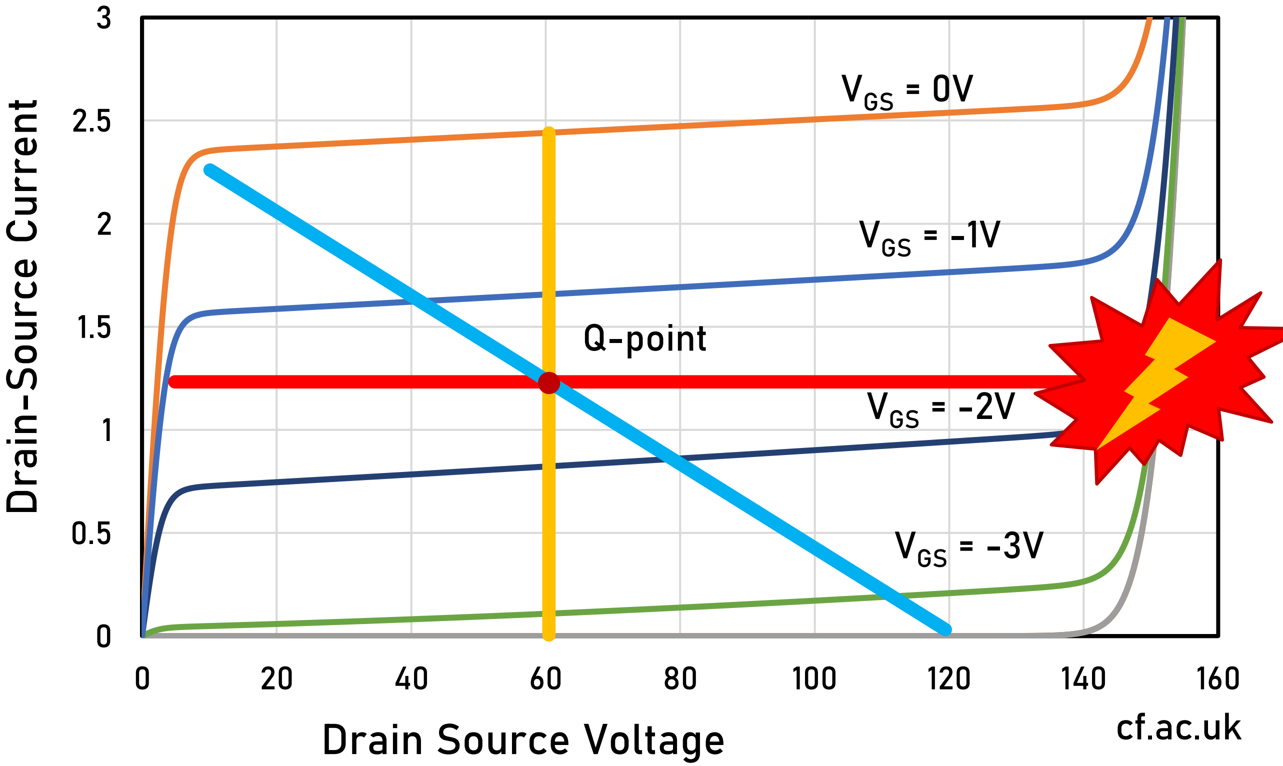
- By changing the gate voltage, the drain current changes -> Controlled current source (surprisingly good model!)
- Voltage developed as a result depends on load impedance
- **Load line plots voltage vs current,** both in one trace
- Quiescent current determines the point around which the load lines form

Transistor



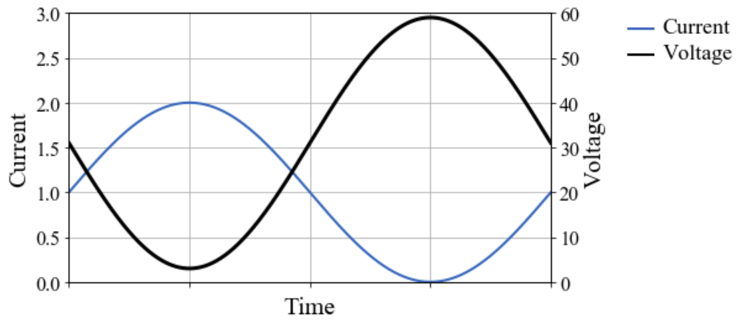


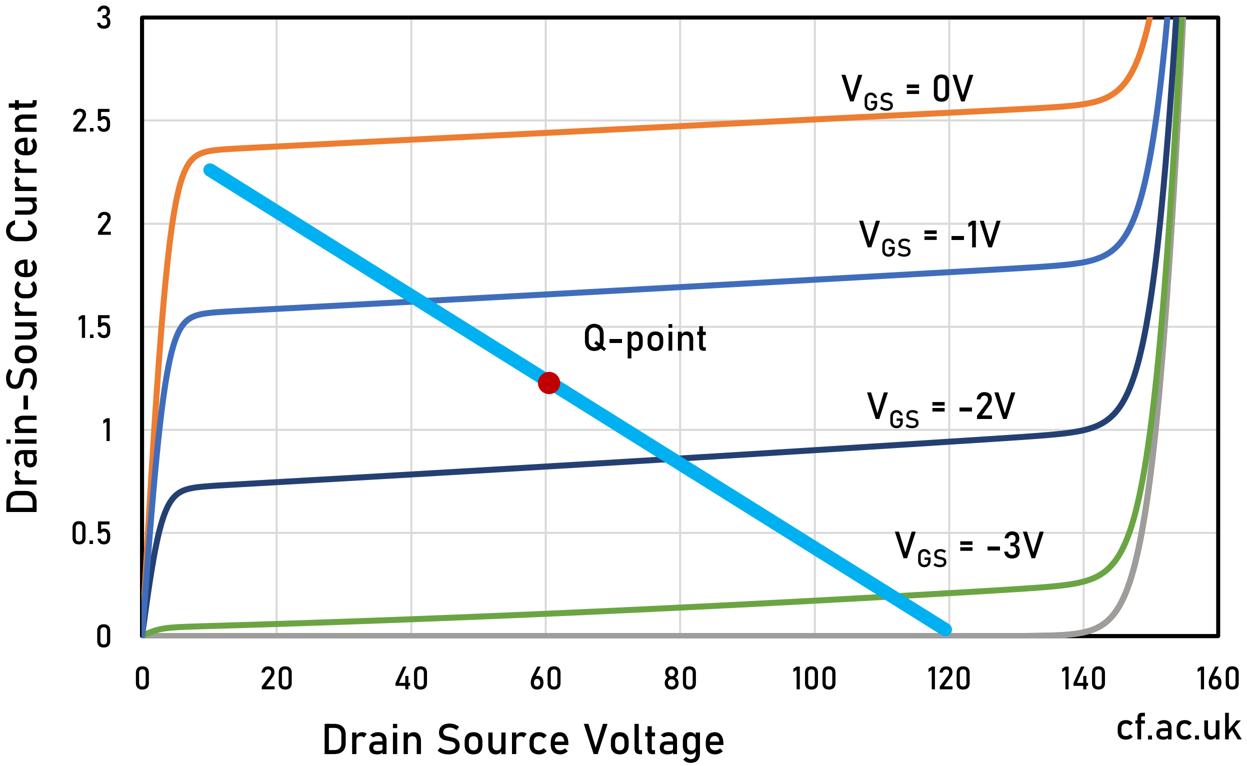


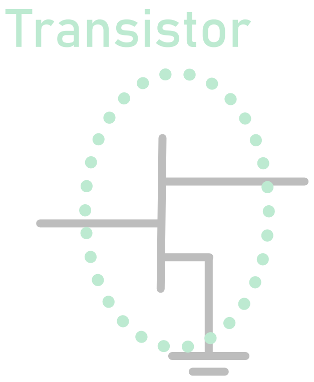


PA classes - Class A

- Remember
  - P = V * I
  - Transistor dissipates power at all points in time!
- But!
- Super linear
- All of the gain
- Amazing if we
  - Can get the heat away
  - Don't have to foot the energy bill

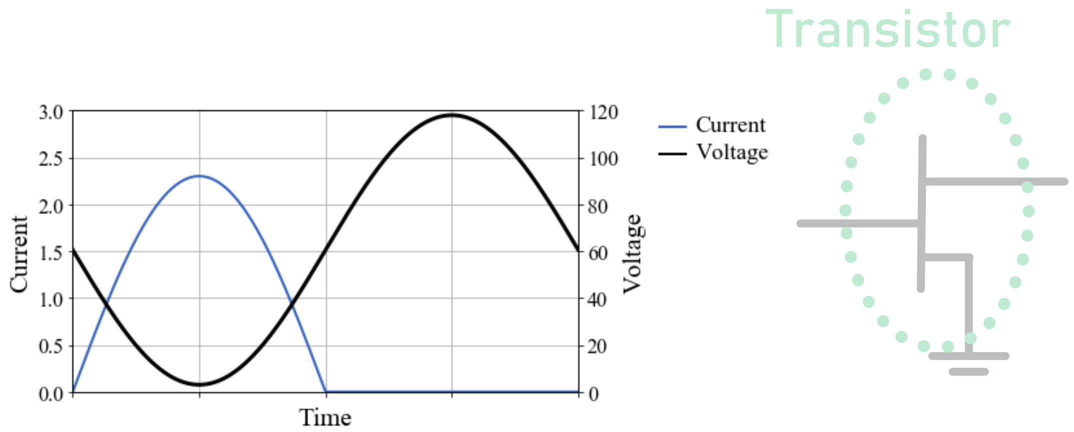


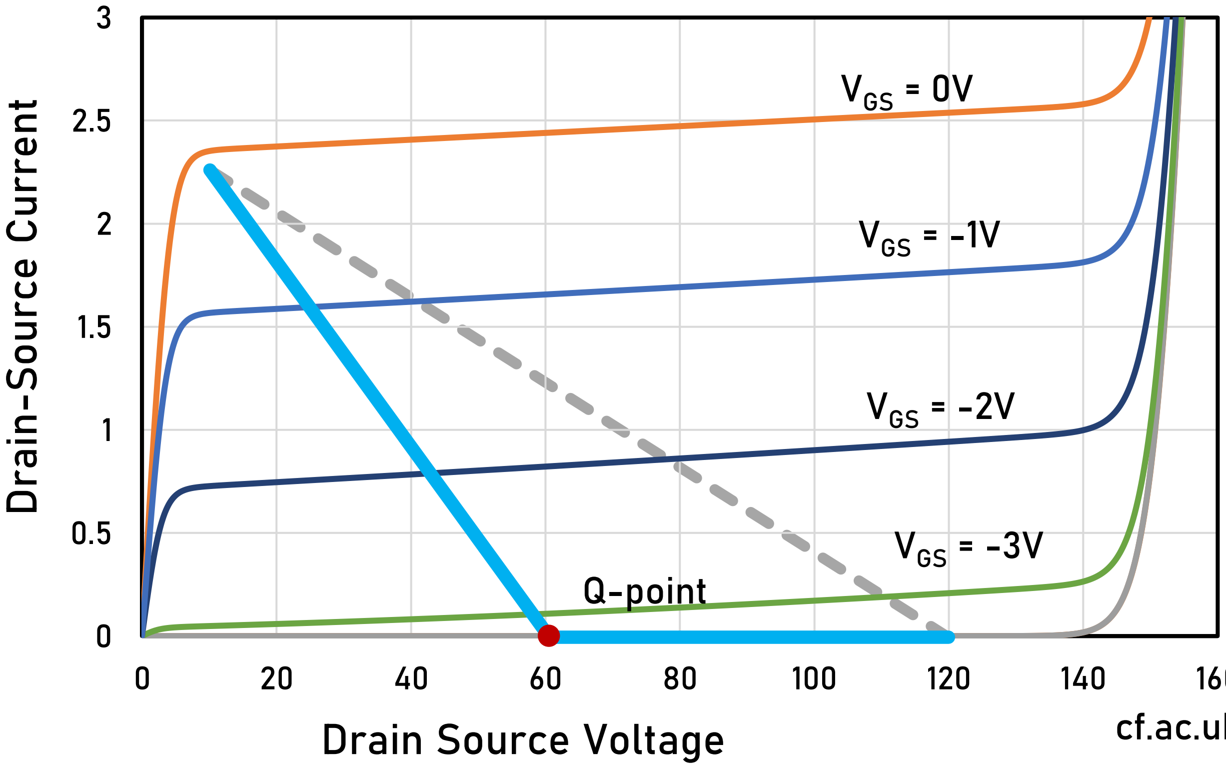




PA classes - Class B

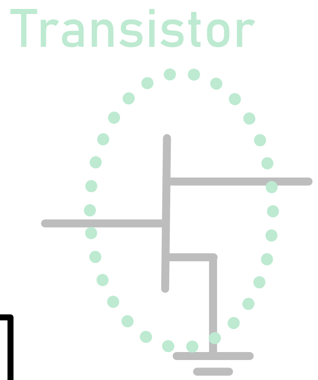
- Same load impedance as class A but load line looks different!
- Assumes perfect short circuit of harmonics
- Transistor has no losses for half the time (ideally)
- Still fairly linear
- Starts at 0 current, needs twice the gate voltage swing -> 6dB less gain



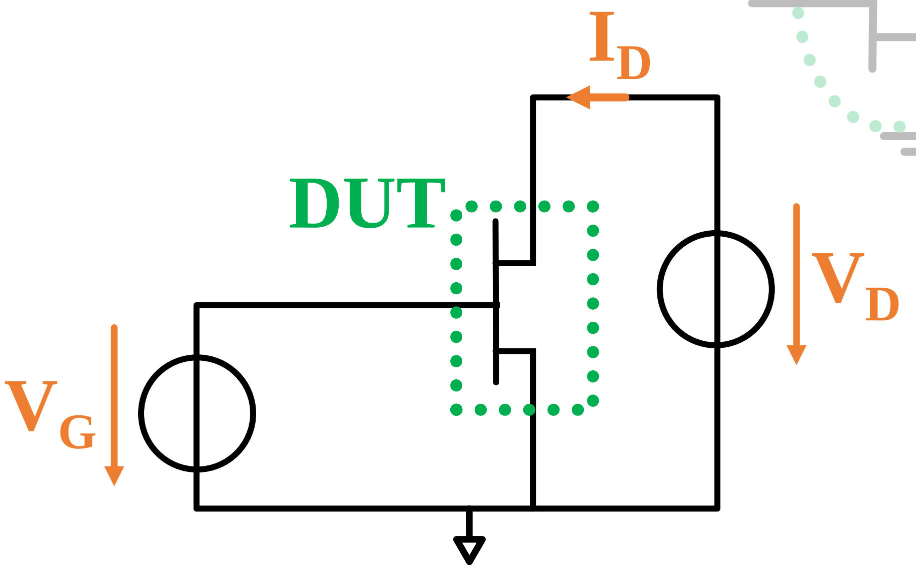


Measuring IV curves

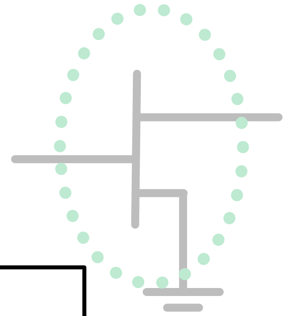
CUARS
Clwb Radio Amatur Prifysgol Caerdydd
Cardiff University Amateur Radio Society
CARDIFF UNIVERSITY
PRIFYSGOL CAERDYDD



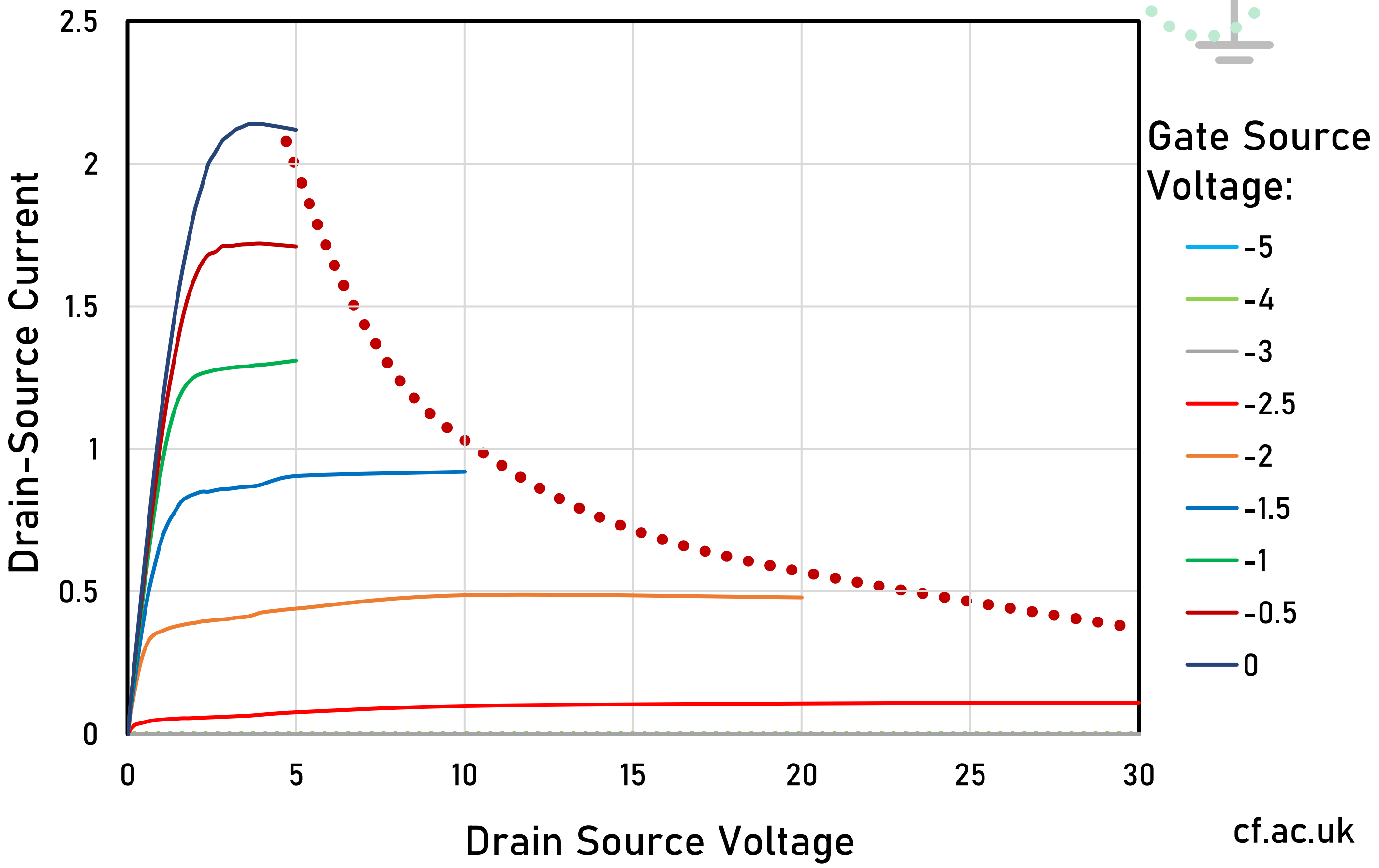
- Very simple measurement:
  - Two adjustable voltage sources
  - One multi-meter to measure the current (plus a second one if you don't trust your voltage source)
- V_D and V_G are swept and I_D is measured
- Need to make sure to stay clear of maximum power (ideally by a lot)
- Also need to stay clear of breakdown voltage (datasheet value is good enough)
- But: Not a big issue, interesting bit is around small drain voltages anyway (max current)



Measuring IV curves

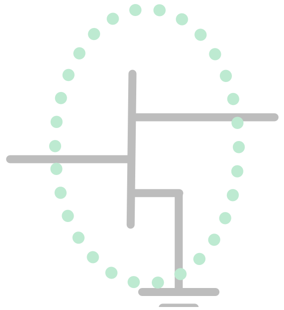


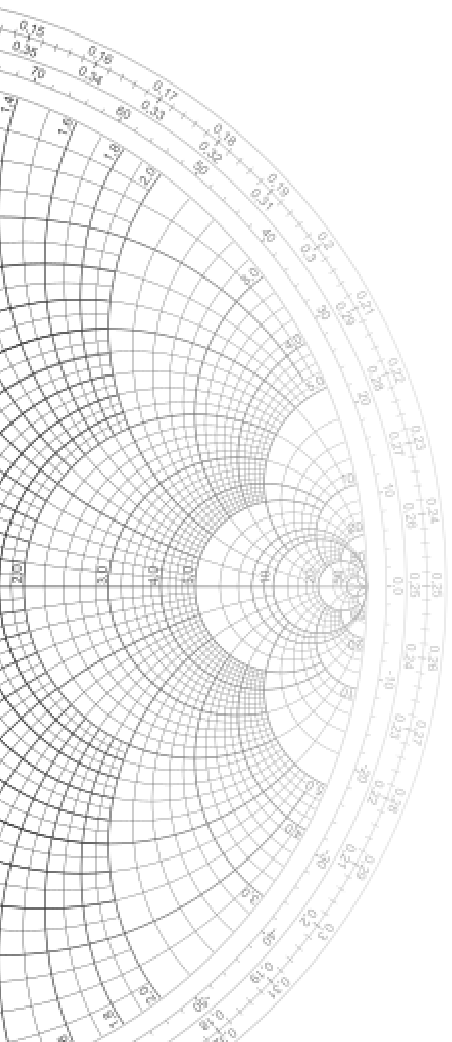
- Measurement result of Wolfspeed 10W GaN HEMT
- Maximum power depends on mounting
- Tried to stay below 10W



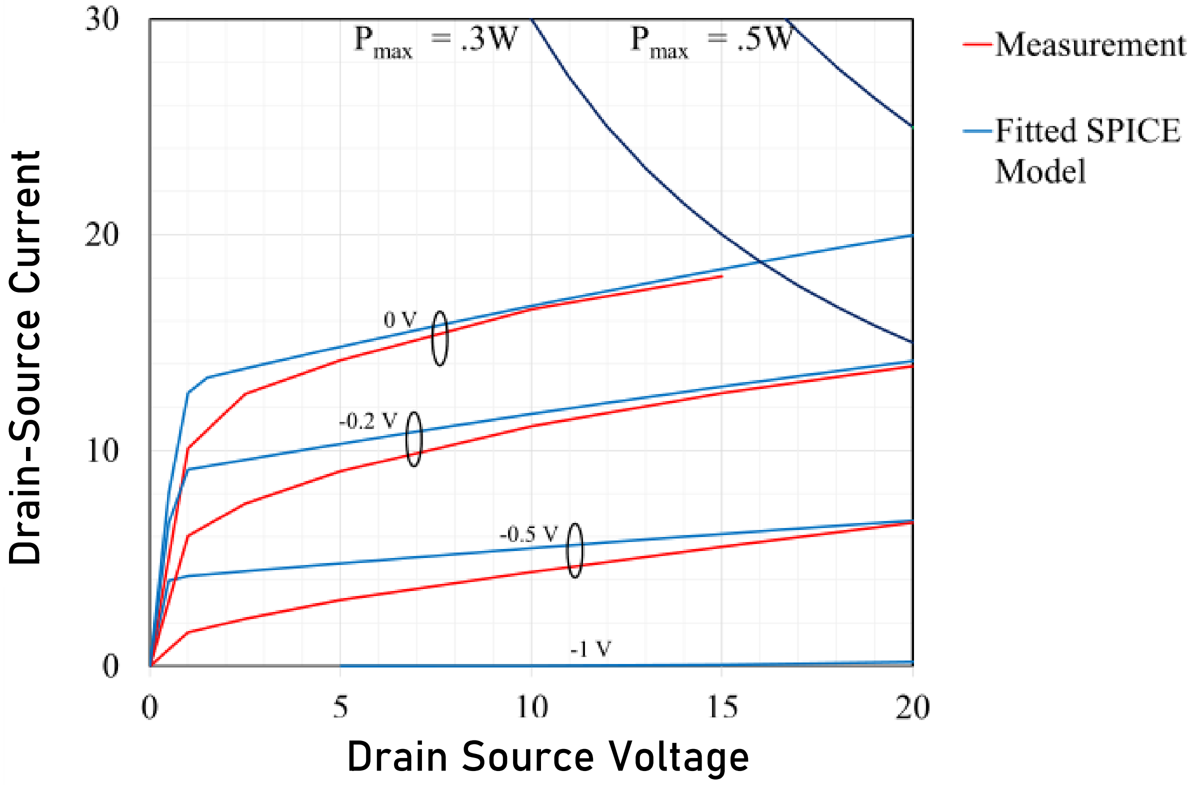
Measuring IV curves

Transistor

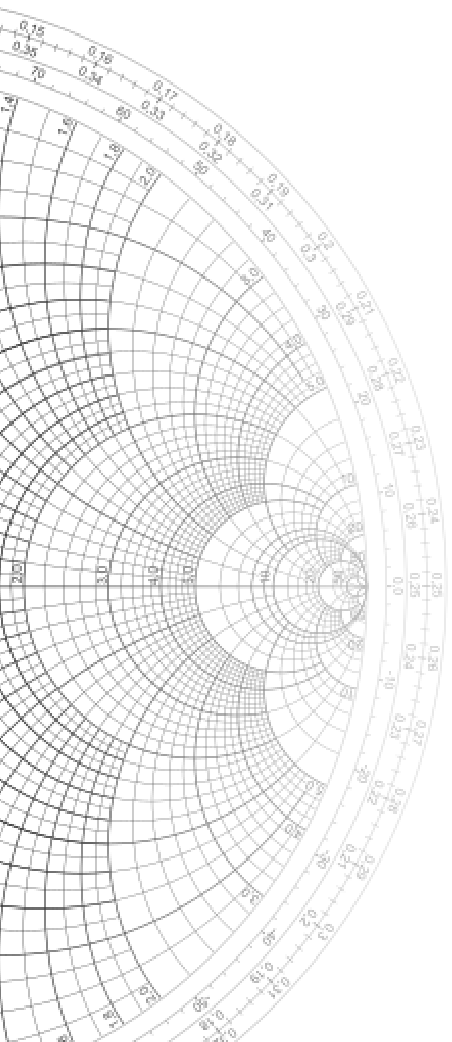




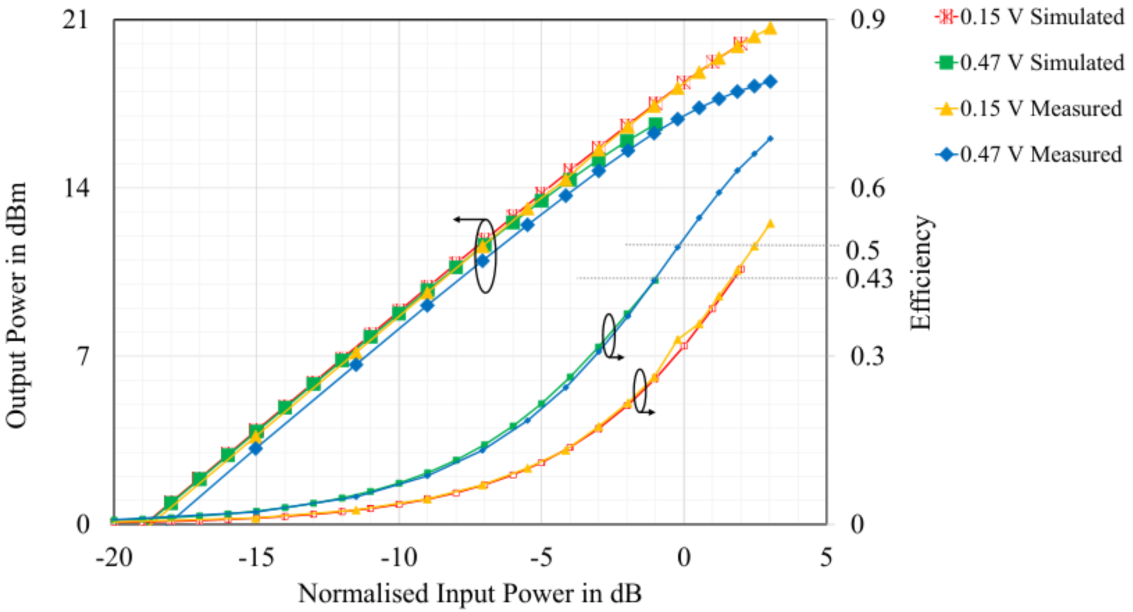
- Measurement of a BF254C JFET
- Can directly design with the IV curves (depending on frequency)
- Can use them to fit a model (eg SPICE)

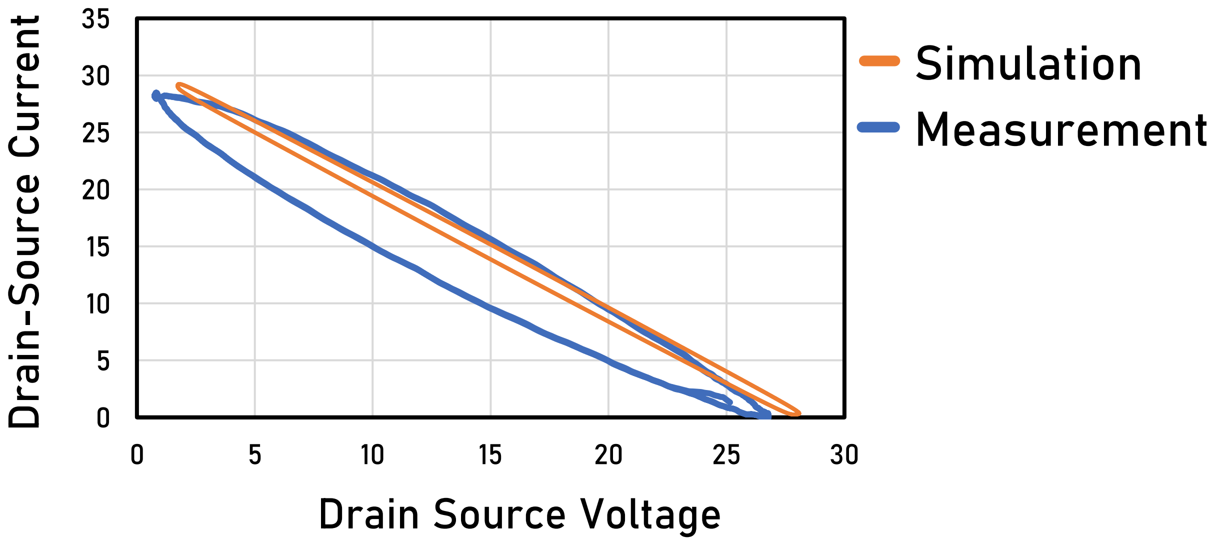


Matching networks



- Using SPICE model or IV curves, matching circuit can be designed and simulated
- Simulation and measurement show good agreement
- The measured load line looks more like an oval...





Not so fast!

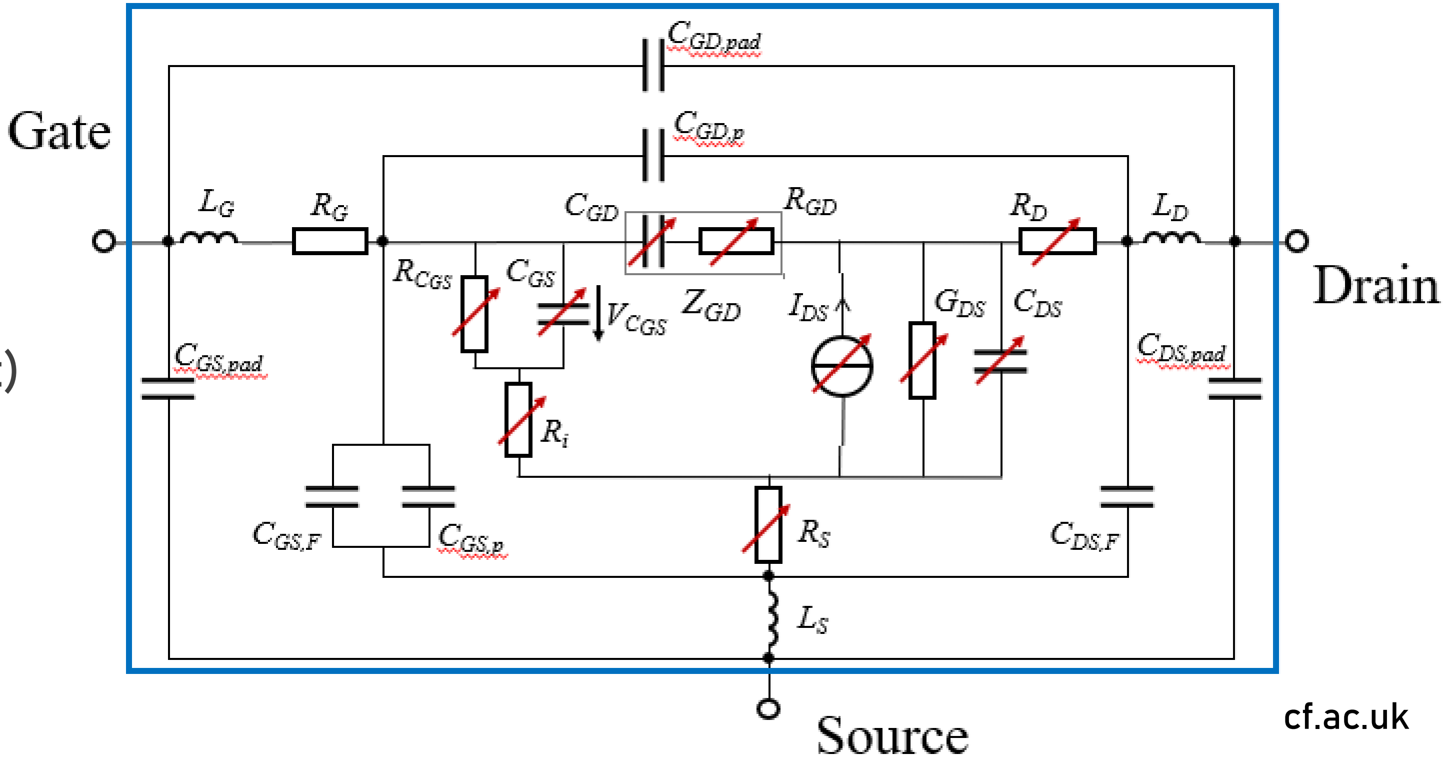
- Sounds all nice and easy and:
- It can be (if we're lucky!)

But

- Physic's getting in the way (as always)
- Transistors are more than just a current source
- Transistors are tiny
- GaN HEMTs start doing weird stuff

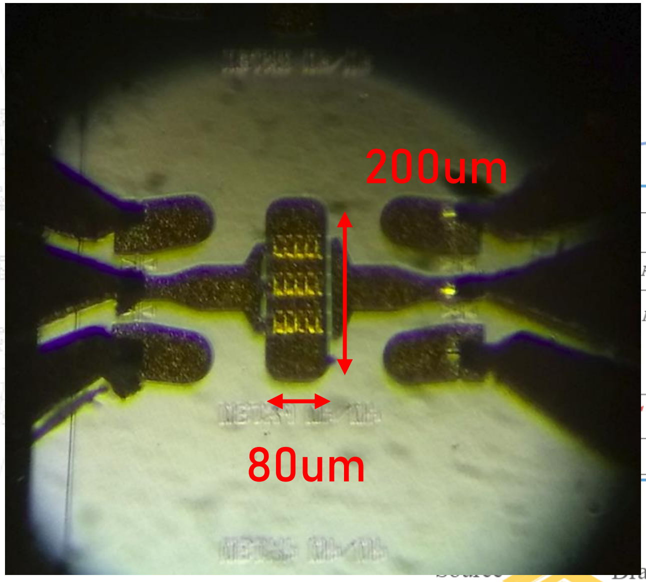
Not just a current source

- Transistors have lots of parasitic effects!
- Depending on frequency might not be that relevant
- Once it becomes relevant, need to deal with it
- If we're lucky someone else already did this and measured the parasitics
- If not we can make educated guesses or resort to load pull (or try manually optimising it)

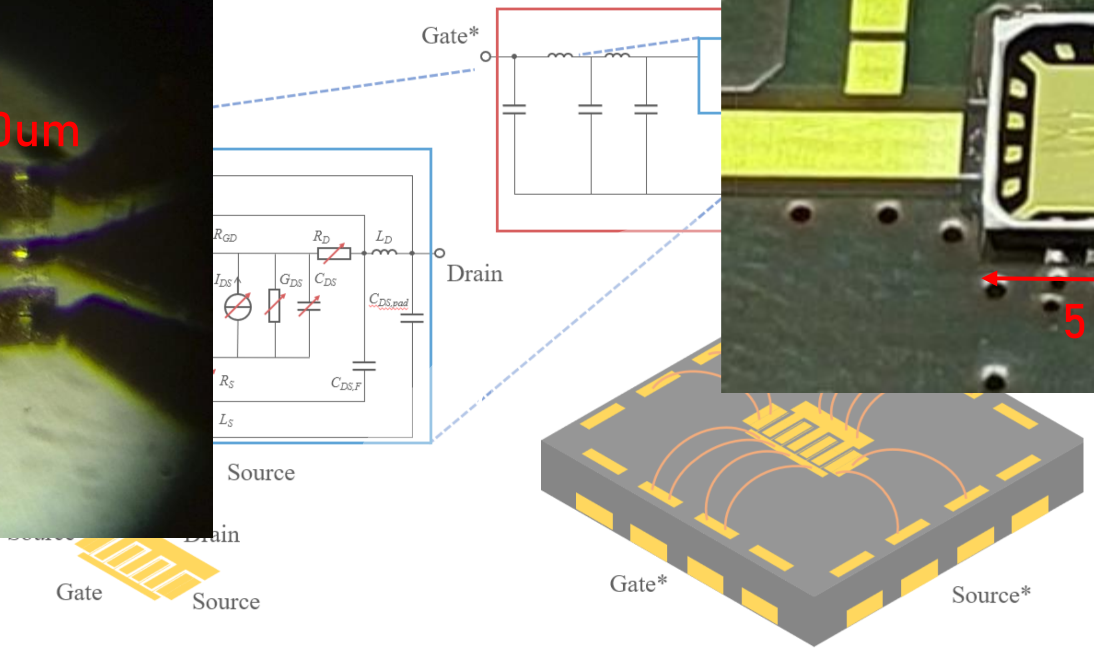


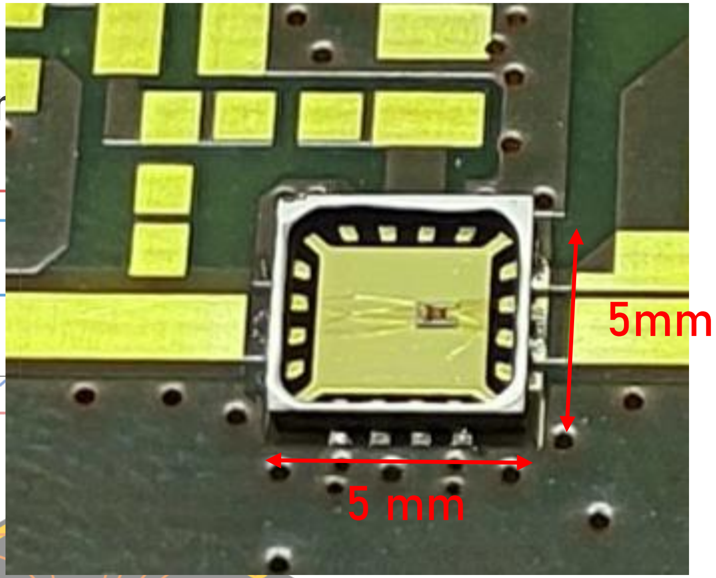
Tiny transistors

- Transistors are typically surprisingly small
- 2kW LDMOS is around 6mm x 25mm, 20W LDMOS .6mm x 2.5mm
- GaN HEMTs are even more compact
- Almost all transistors are packaged, adds mor



3 W device

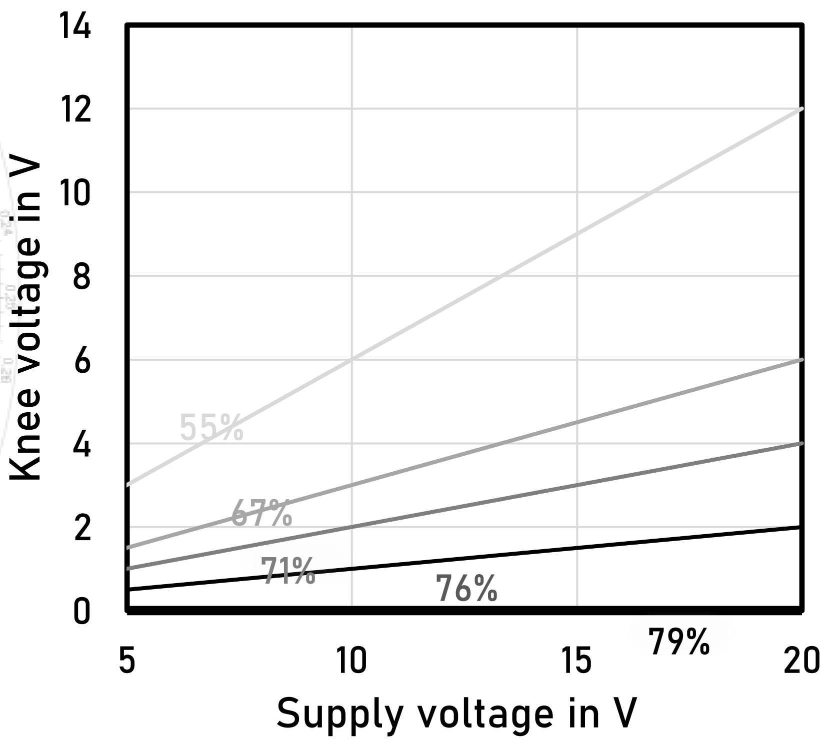


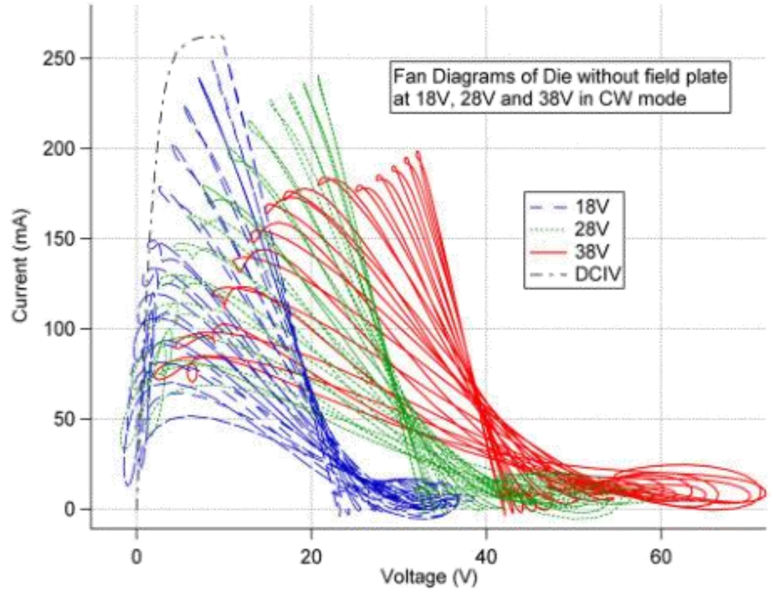


6 W device

GaN transistors and the linear region

- In GaN HEMTs, electrons get trapped by high electric fields, that increases the size of the linear region (or knee region)
- This gives us less voltage to work with and thus lower power and efficiency
- This effect is invisible when doing normal DCIV measurements



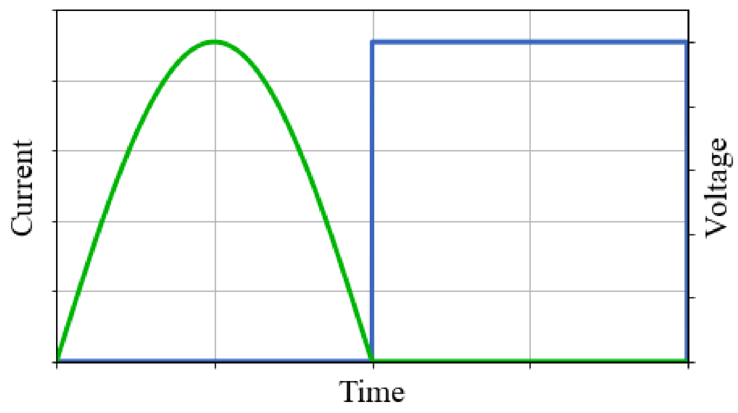


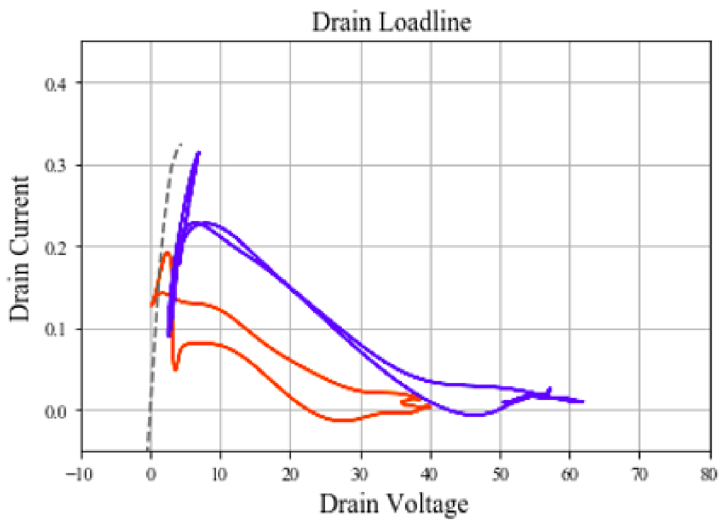
Advanced RF IV Waveform Engineering Tool for use in device technology optimization: *RF Pulsed Fully Active Harmonic Load Pull with Synchronized 3eV Laser*

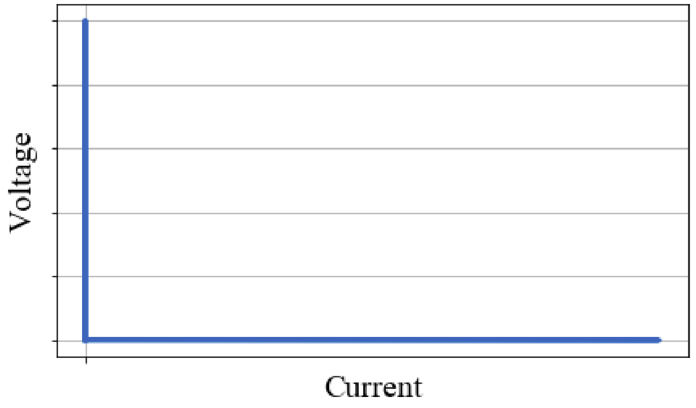
M.A. Casbon, P.J. Tasker, Wei-Chou Wang*, Che-Kai Lin*, Wen-Kai Wang*, W. Wohlmuth*

Getting the Efficiency up

- Class F, class E, class D, class X (really!)
- Reducing voltage current overlap
- In load lines: No voltage if current non-zero and vice versa
- Realistically, 70% - 85% are achievable (depending on frequency)

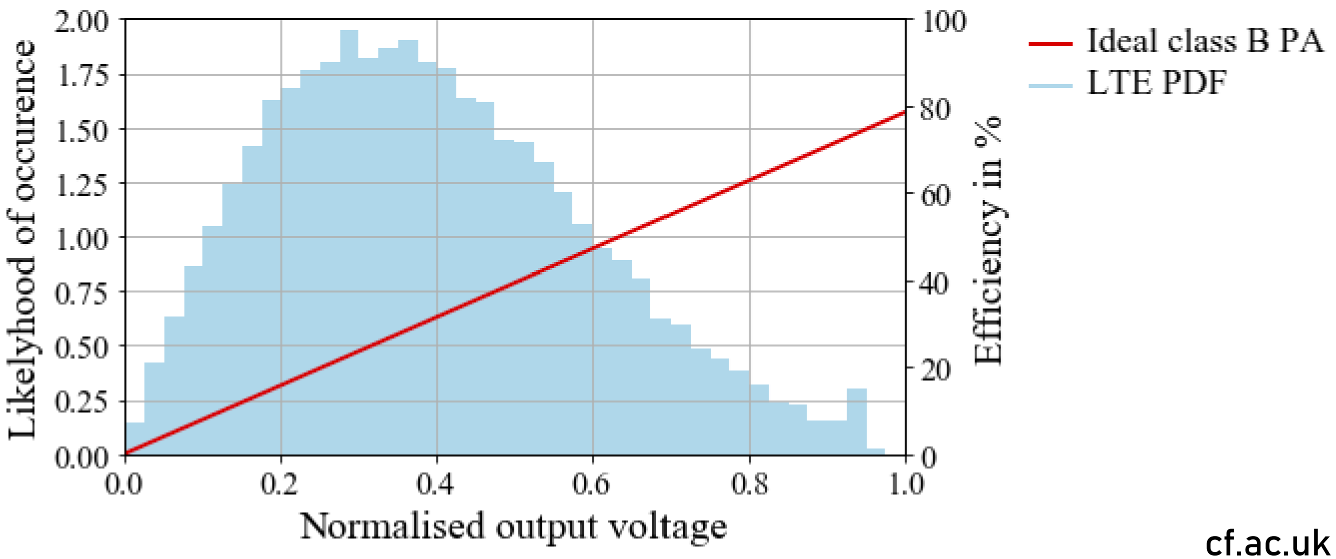






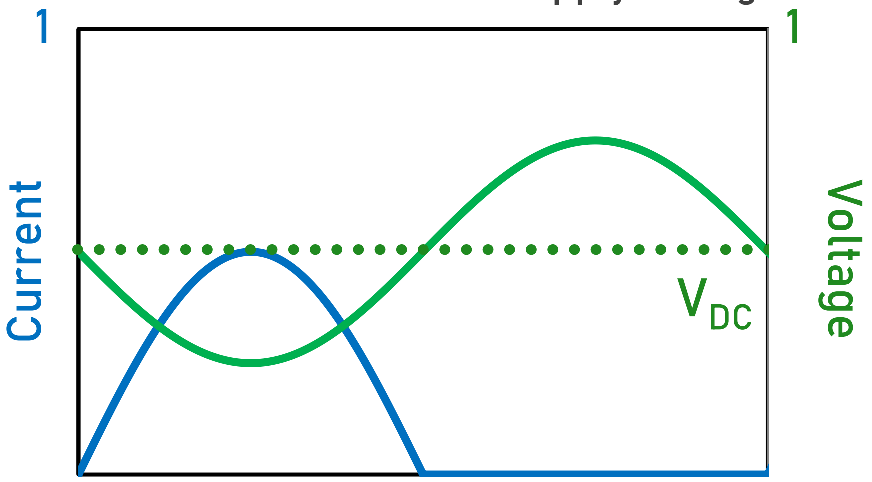
Keeping Efficiency high

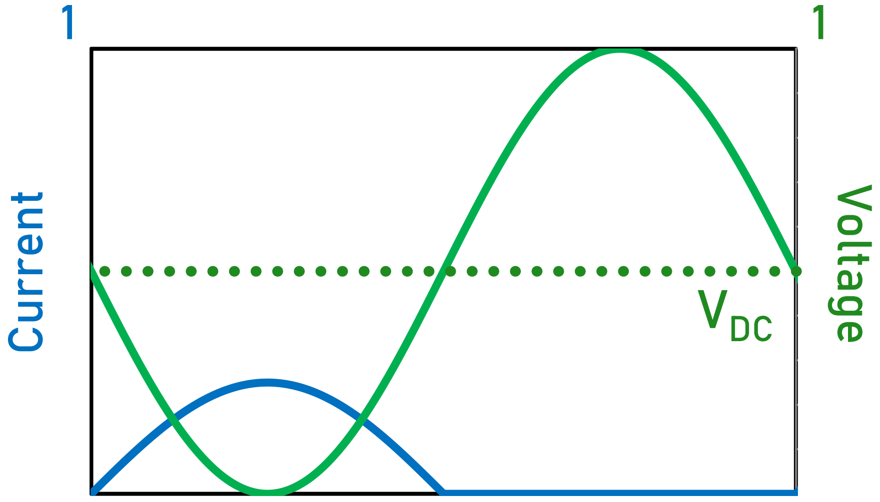
- Most modulation schemes operate PA in back-off
- Operate at relatively low output power most of the time but need to be able to provide high powers at the same time
- Unfortunately, PA is very inefficient there

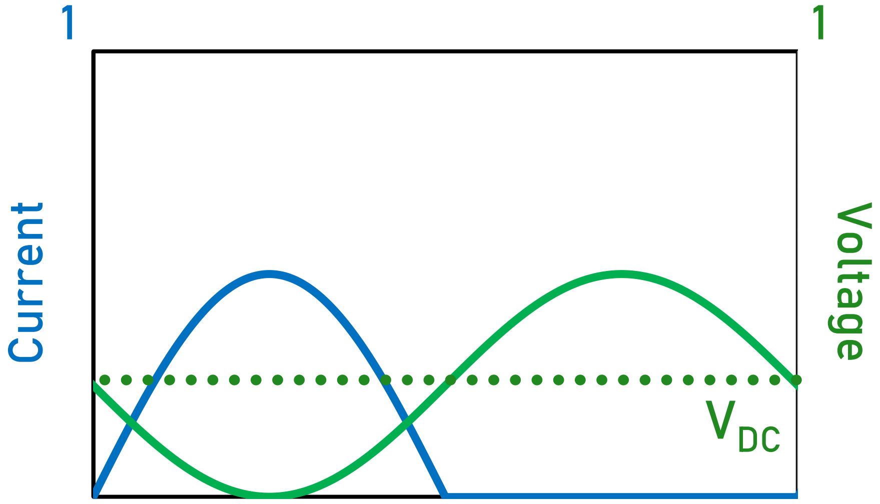


Keeping Efficiency high

- Inefficiency due to voltage not reaching knee
- Can be fixed by introducing additional transistors
  - To modulate the RF load impedance
  - To modulate the supply voltages

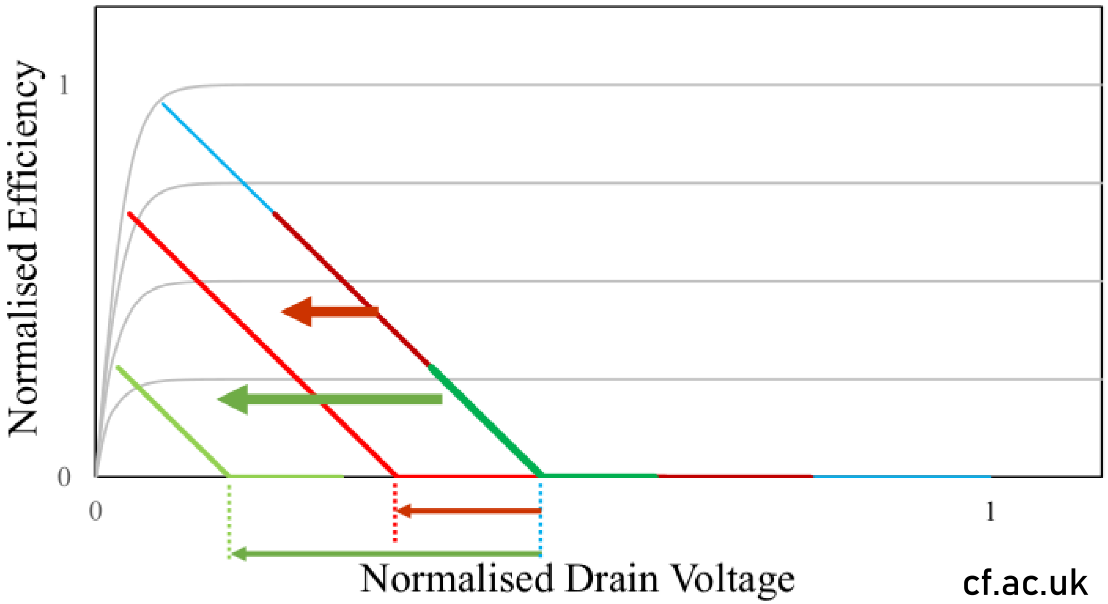






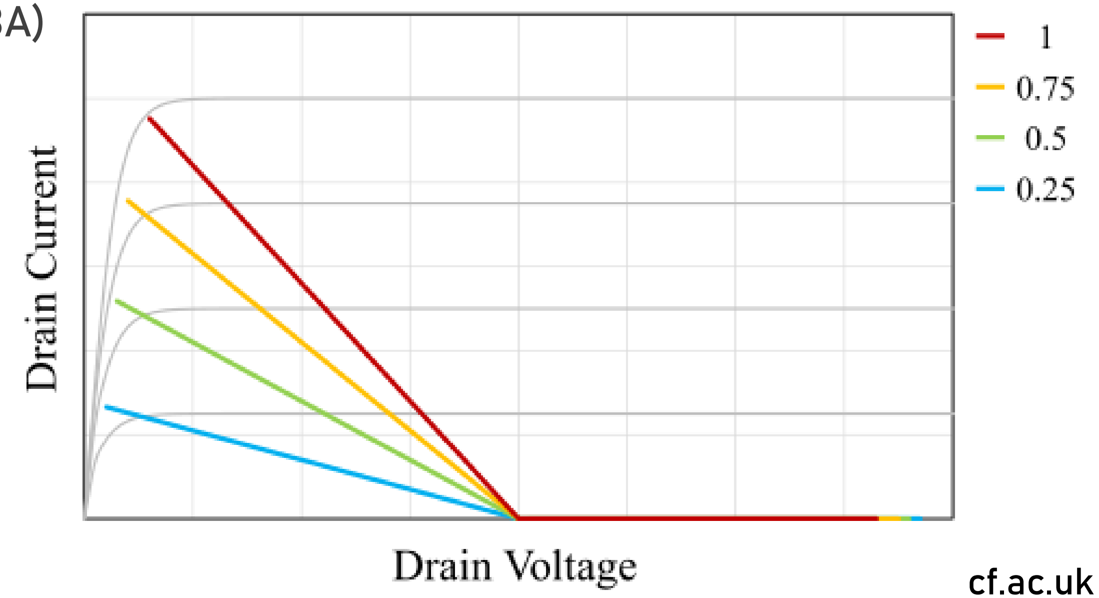
Supply Modulation

- Constant RF load impedance
- Change supply voltage with modulation
- Keep voltage swing but move minimum closer to knee region
- Requires the supply voltage to change
  - Easy for slow signals
  - Very challenging for modulation frequencies in modern communication systems



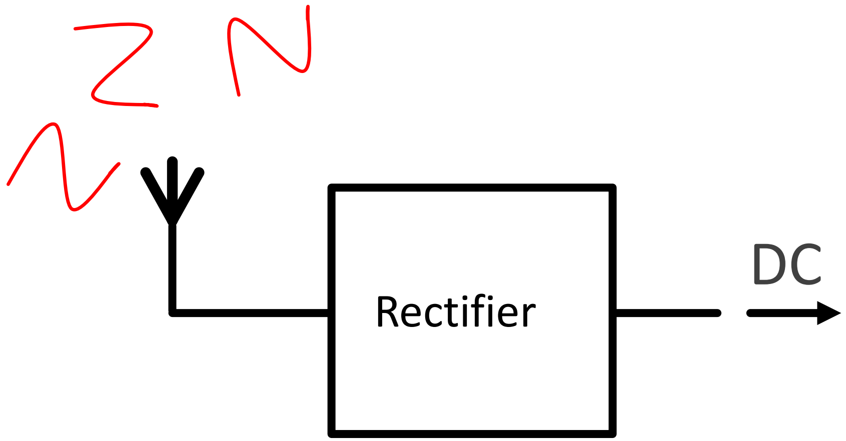
Load Modulation

- Constant supply voltage
- Change in load impedance reduces losses
- Keeps PA efficient over large power ranges
- Different ways to realise it
  - Use two amplifiers (Doherty, outphasing)
  - A balanced PA and a control signal (LMBA)
  - Adjustable matching network (passive load modulation)



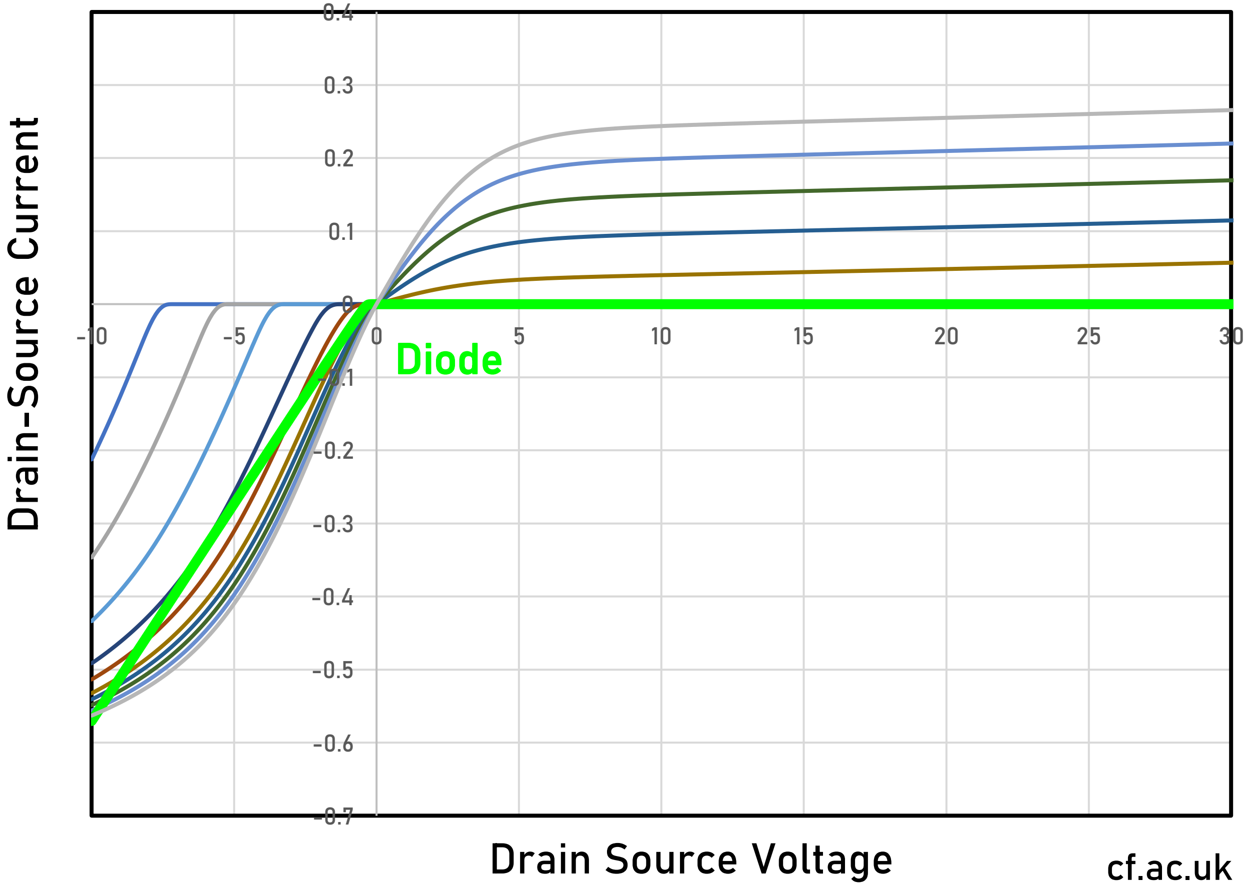
Rectifiers

- Convert RF power to DC power
- Ubiquitous RF power -> Many applications
  - Energy harvesting
  - Wireless power transmission
  - RF DC/DC converters



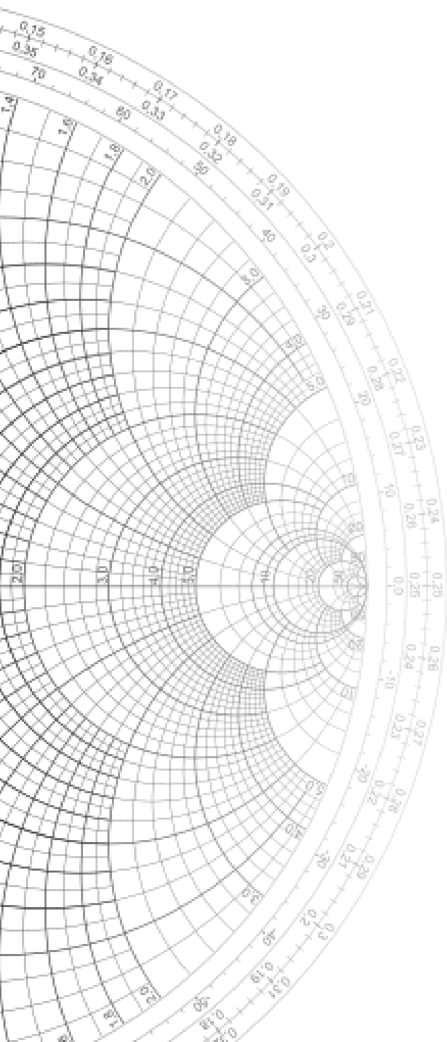
Rectifiers

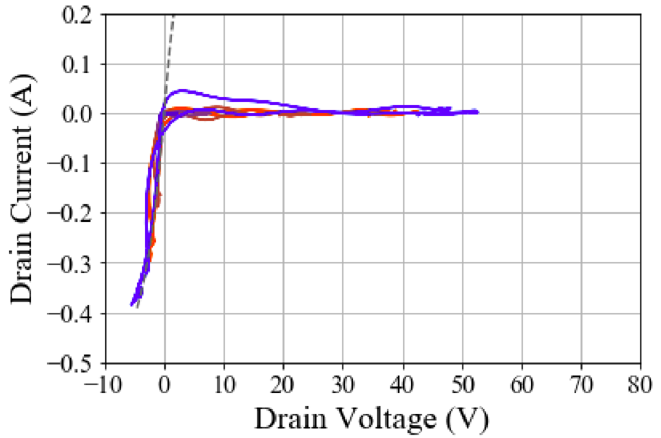
- Can use diodes or transistors (depending on technology!)
- Transistors allow higher efficiencies at RF, over 90% RF -> DC efficiency but they need gate signal (depending on technology!)
- IV curves now extend to negative drain source voltages

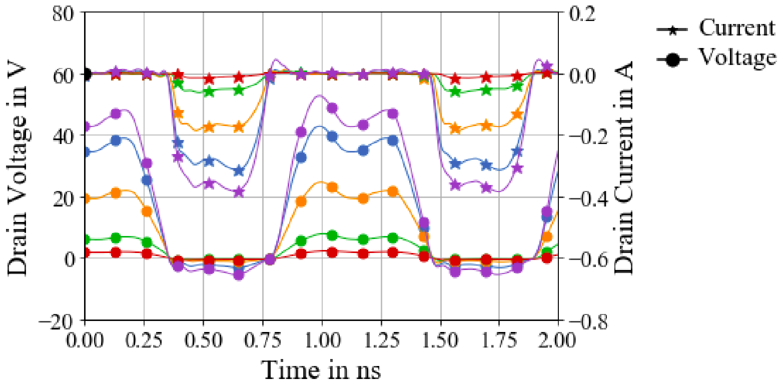


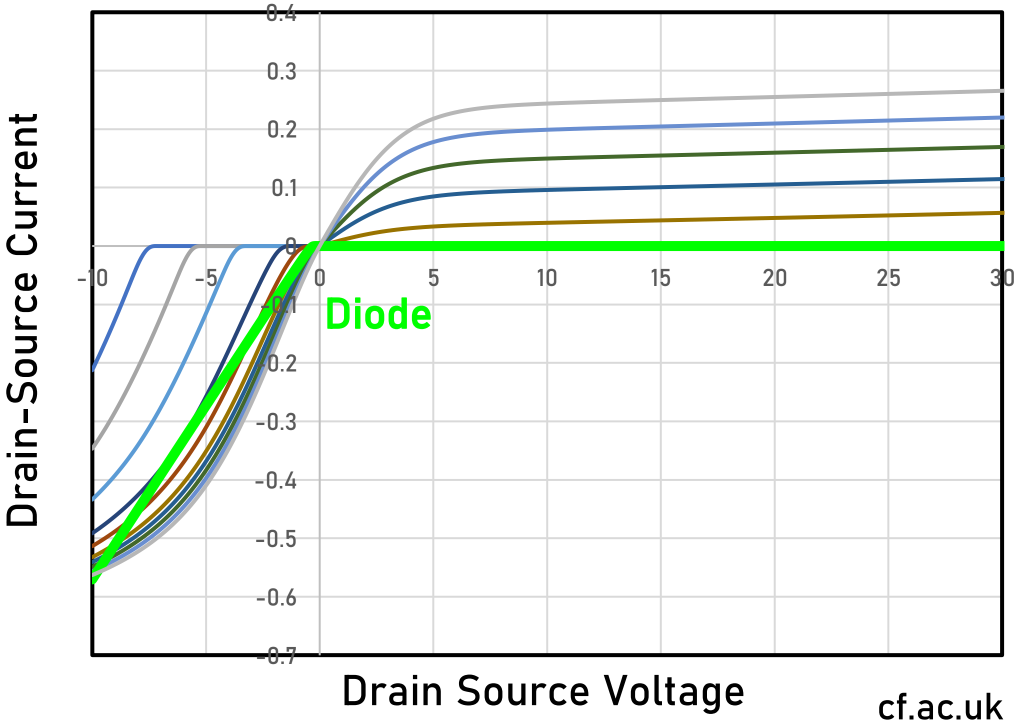
Rectifiers

- We have load-lines in rectifiers, both diode and transistor based ones!









Conclusion

- Loadlines are a useful tool to visualise voltage and currents of transistors
- Can be used in a wide range of applications
- Using simple measurements, a lot of information about a transistor can be obtained
- This can be used to design PAs or form the basis for the basis for

Thanks for listening!

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