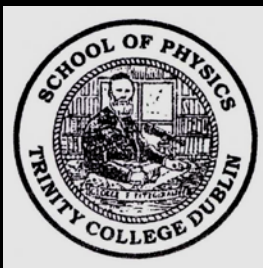
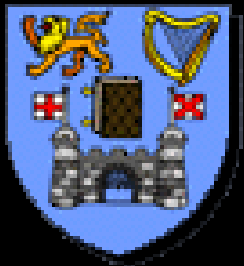


Semiconductor Devices - 2014

*Lecture Course
Part of
SS Module PY4P03*

Dr. P. Stamenov

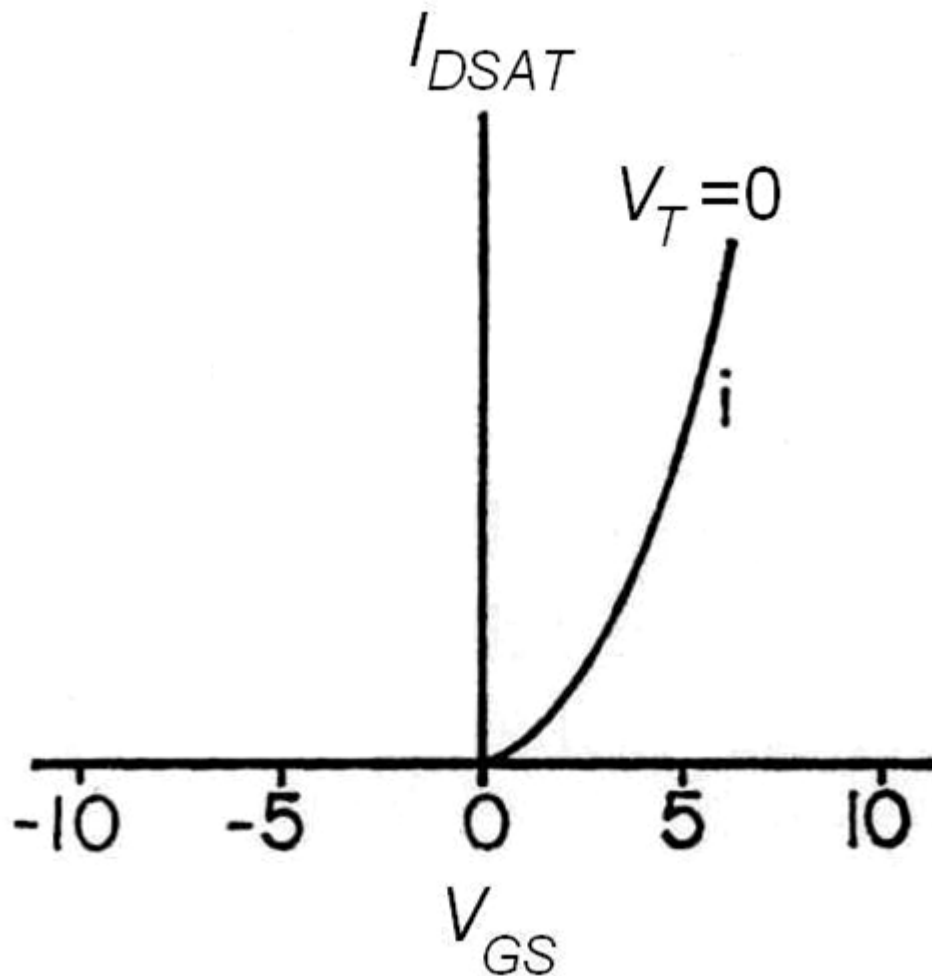
School of Physics and CRANN, Trinity College,
Dublin 2, Ireland



Hilary Term, TCD
3th of Feb '14

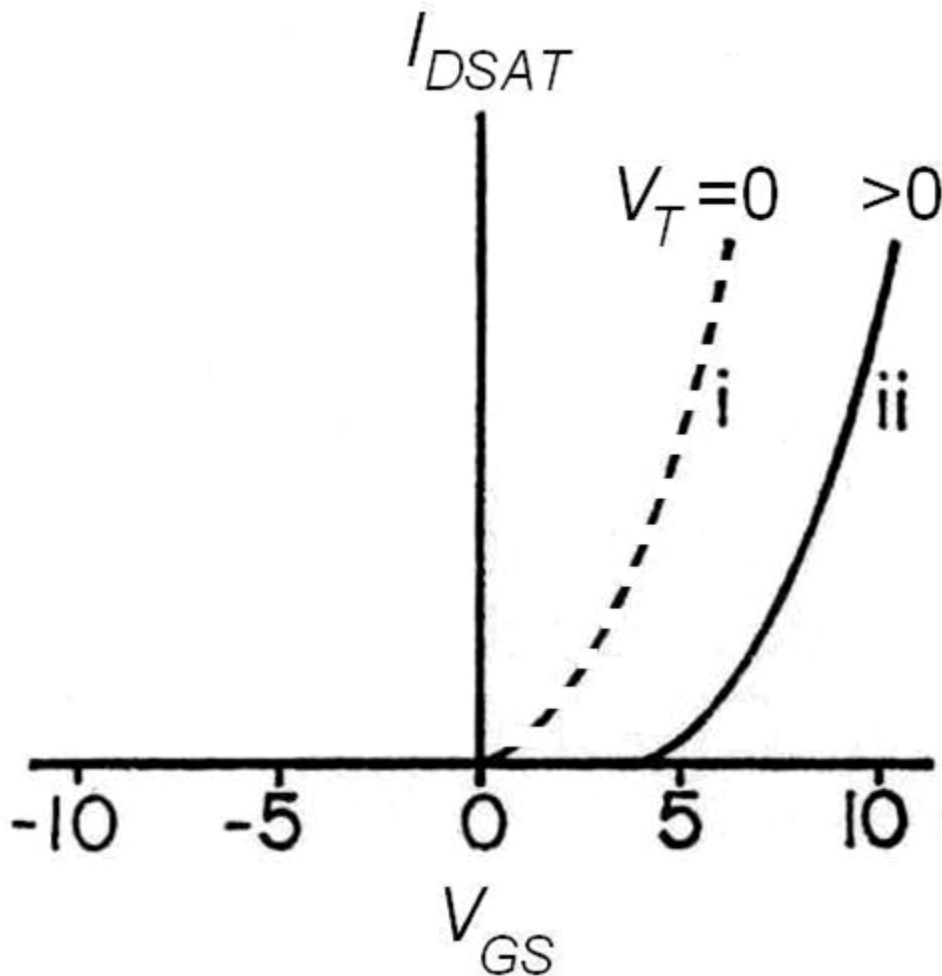


MOSFET – Unmodified Channel



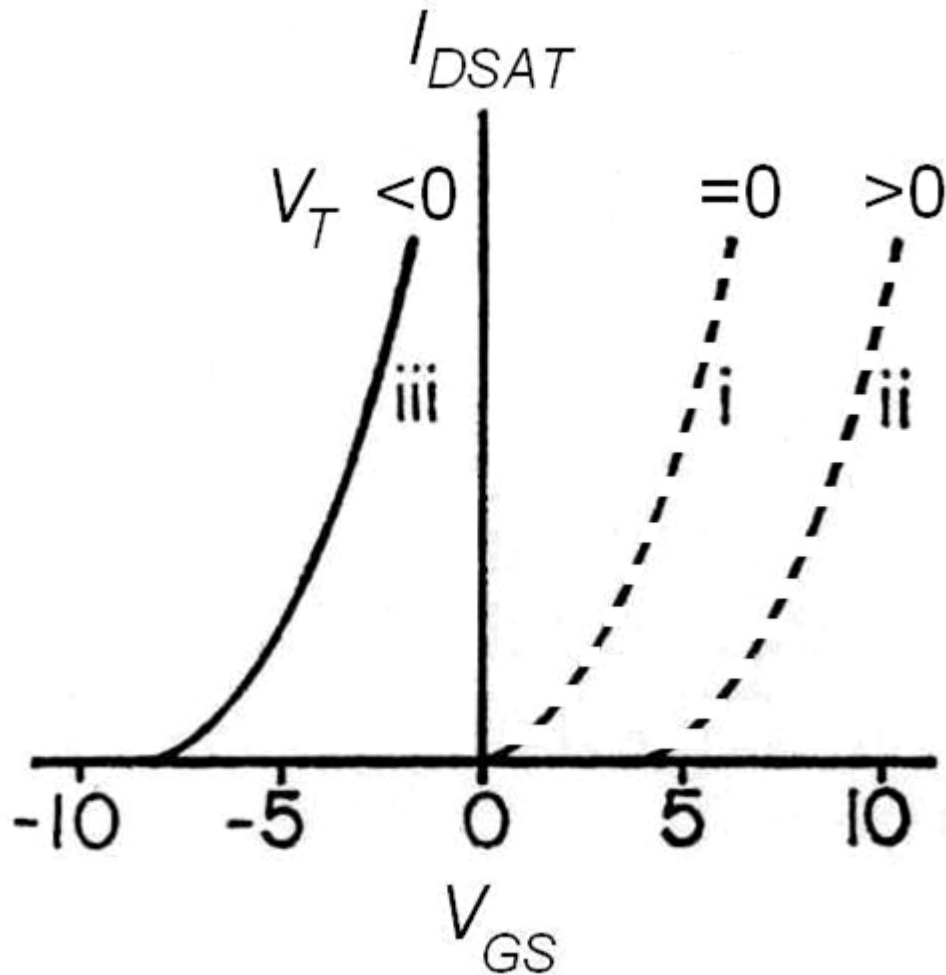
- Shown for threshold voltage \sim pinch-off voltage close to zero ($V_{th} \sim V_p = 0$).
- The curve is a parabola in the ideal case.
- Cannot be used readily close to zero input bias.
- Neither normally-on, nor normally-off.
- Not well defined state for switching applications
- Cheap and cheerful (no channel doping adjustment steps)

MOSFET – Enhancement Mode



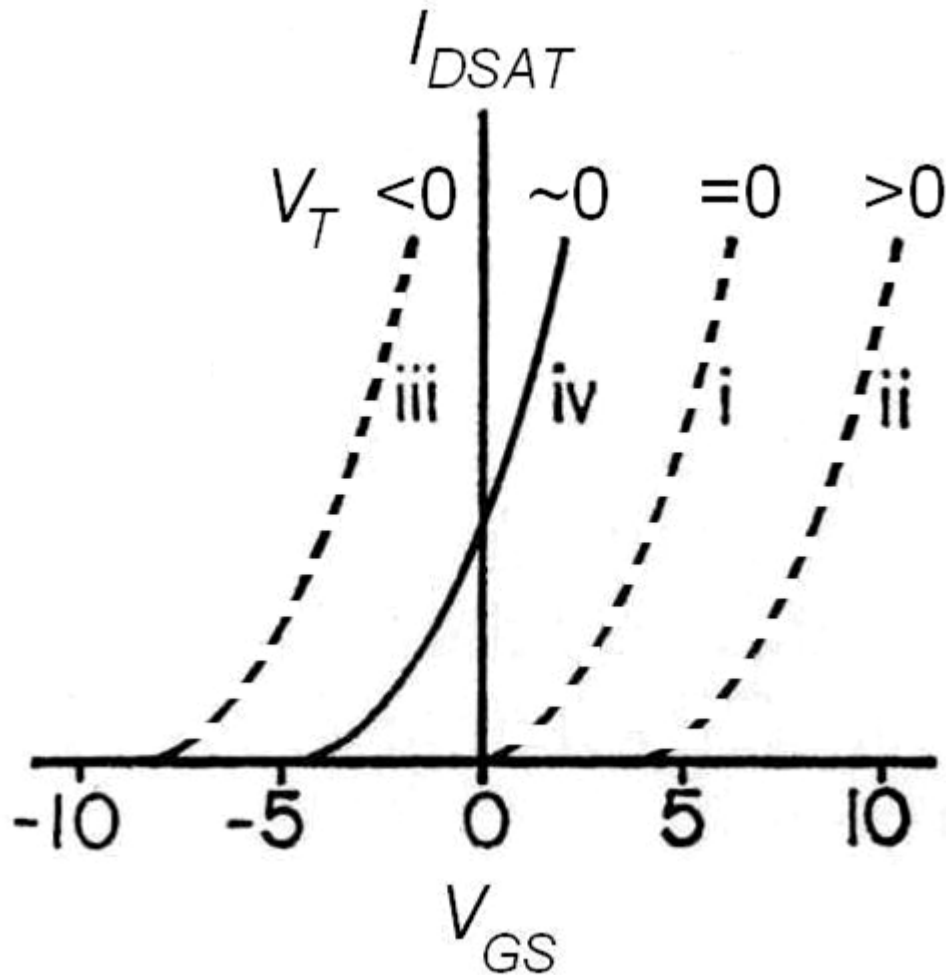
- States (acceptor) deliberately introduced – (say by B-doping).
- Shown for threshold voltage \sim pinch-off voltage close to zero ($V_{th} > 0$).
- The curve is a parabola in the ideal case.
- Cannot be used readily close to zero input bias.
- Normally-off.
- Well defined state for switching applications

MOSFET - Depletion Mode



- States (donor) deliberately introduced – (say by P-doping).
- Shown for threshold voltage \sim pinch-off voltage close to zero ($V_{th} > 0$).
- The curve is a parabola in the ideal case.
- Cannot be used readily close to zero input bias.
- Normally-on.
- Well defined state for switching applications

MOSFET – Enhancement-Depletion



- States (donor) deliberately introduced – (say by P-doping) – to the right level.
- Shown for threshold voltage \sim pinch-off voltage close to zero ($V_{th} > 0$).
- The curve is a parabola in the ideal case.
- Can be used readily close to zero input bias.
- Normally-on (in control).
- Good for amplification applications.

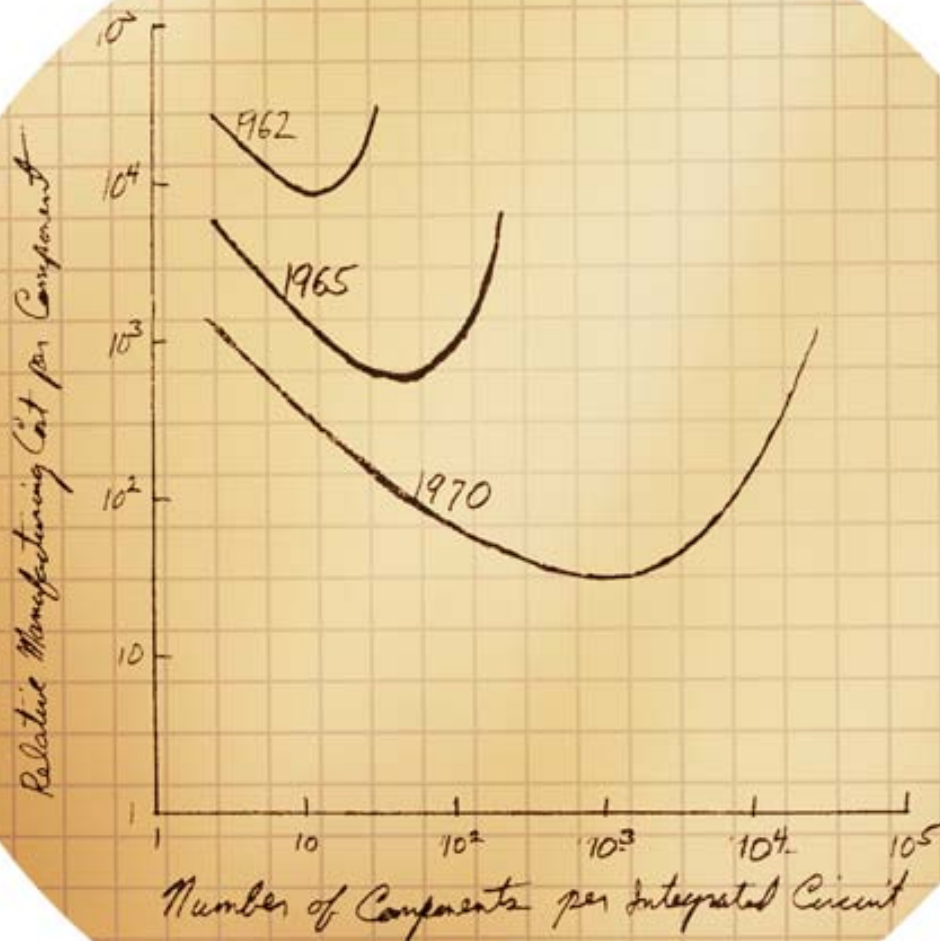
Notes on MOSFET Scaling

- Made smaller and smaller all the time, because of cost, size, speed, power consumption.
- Gate lengths (correspondingly channel lengths) of less than $L < 30$ nm. 15 nm is to be brought in, shortly.
- Together with strain control (to be discussed later) this gives better bandwidth (~ 10 GHz) and faster switching speeds.
- Also allows for higher lateral packing densities in integrated circuits (see below). This is important for both memory and logic applications.
- As channel lengths get progressively shorter, the response deviates more and more from the idealized 'long-channel' model. Tight gate control becomes progressively important and critical for switching applications.
- Despite the favourable scaling of the speed of the MOSFET with size, in particular for CMOS, most competing transistor technologies are even faster. What 'wins' is the combination of qualities.

Integrated Circuits

- While discrete diodes and transistors made the electronic circuits of the 1950's smaller, cheaper to produce and run and more reliable than those created using vacuum 'tubes', some problems remained.
- The cost of executing the numerous interconnections between components remained high and the reliability of the connections to casings remained poor.
- With the development of the integrated circuit technology in the 1960's, all (really true only for digital electronics) could be simultaneously produced on the surface of semiconductor wafers (mostly silicon). There are a number of advantages, to name just few:
 - Smaller circuit size and power consumption
 - Better reliability and overall performance
 - Very low cost when in mass production
 - Real industrial-scale processing (enabled electronics as we know it)

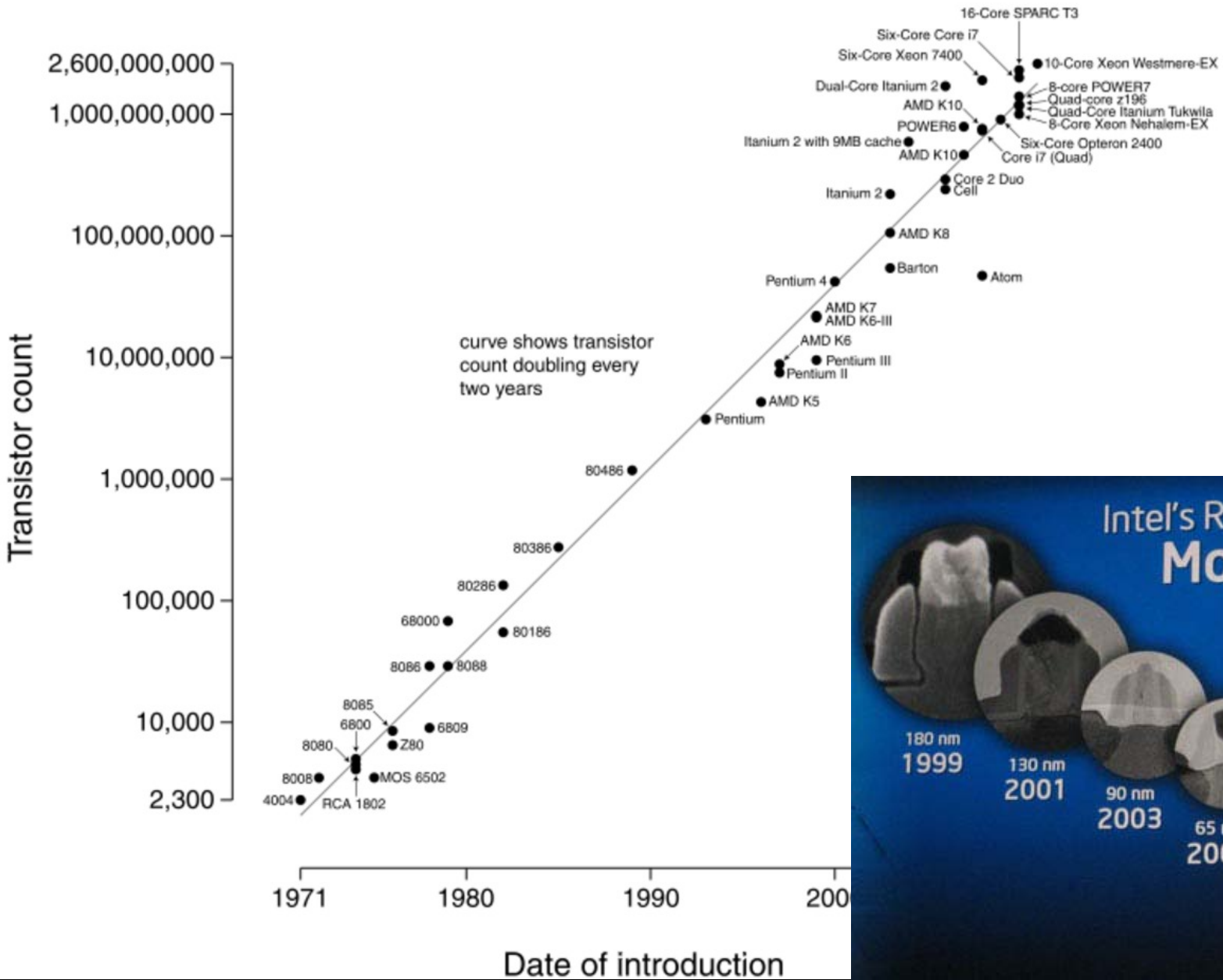
Moore's Law



- Coined by Intel's co-founder Gordon E. Moore in 1965.
- The original discussion was very focused on cost.
- Later on the meaning was refocused on scaling and performance.
- The actual 'doubling time' is closer to 18 months, and it is not clear 'who drives who' – 'It's the Law'

Microprocessor Transistor Counts 1971-2011 & Moore's Law

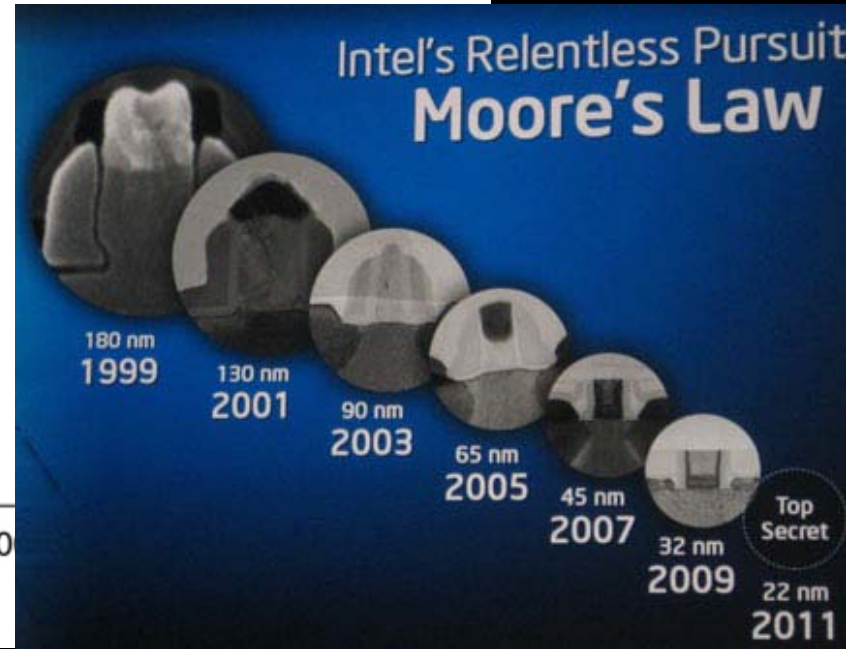
More Moore



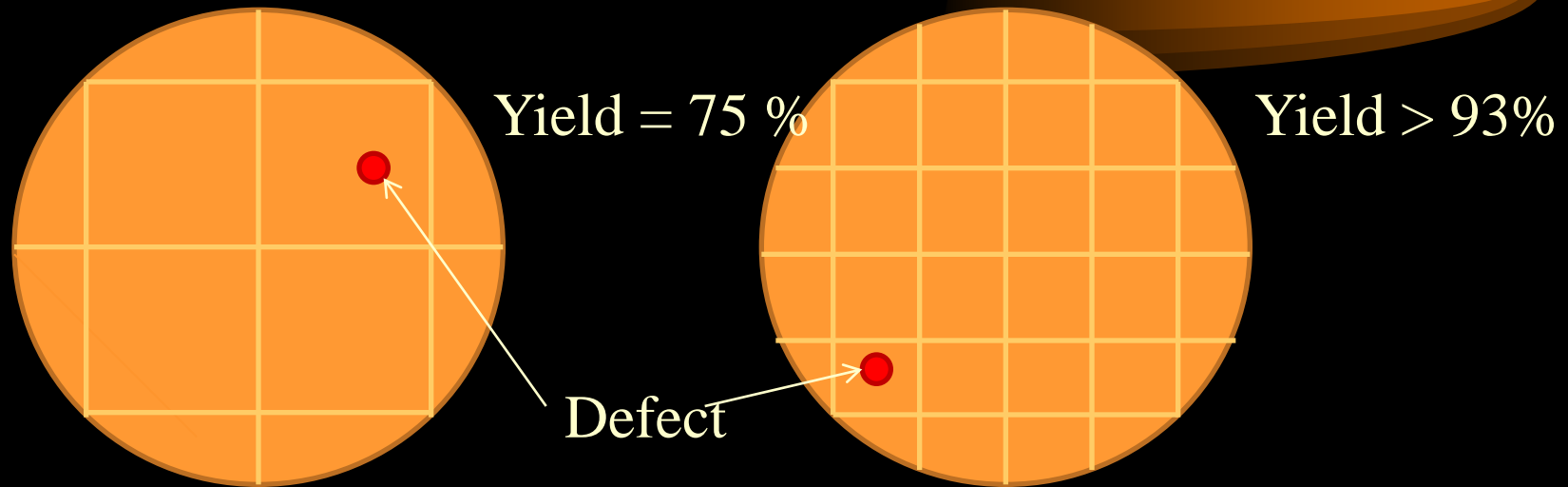
$$\frac{1}{\sqrt{2}} \cdot 180 = 127$$

$$\frac{1}{\sqrt{2}} \cdot 130 = 92$$

$$\frac{1}{\sqrt{2}} \cdot 90 = 64$$

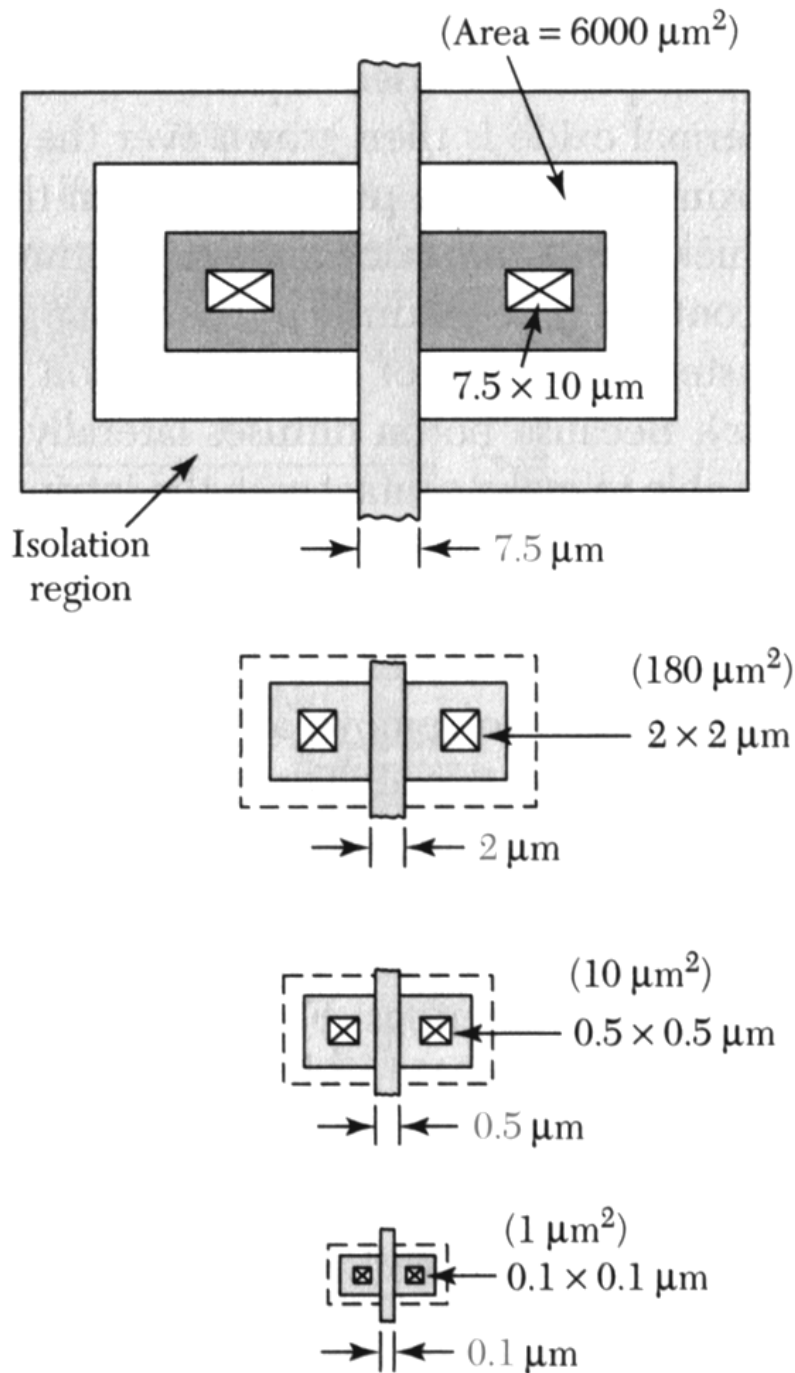


Component Size, Die Size, Wafer Size



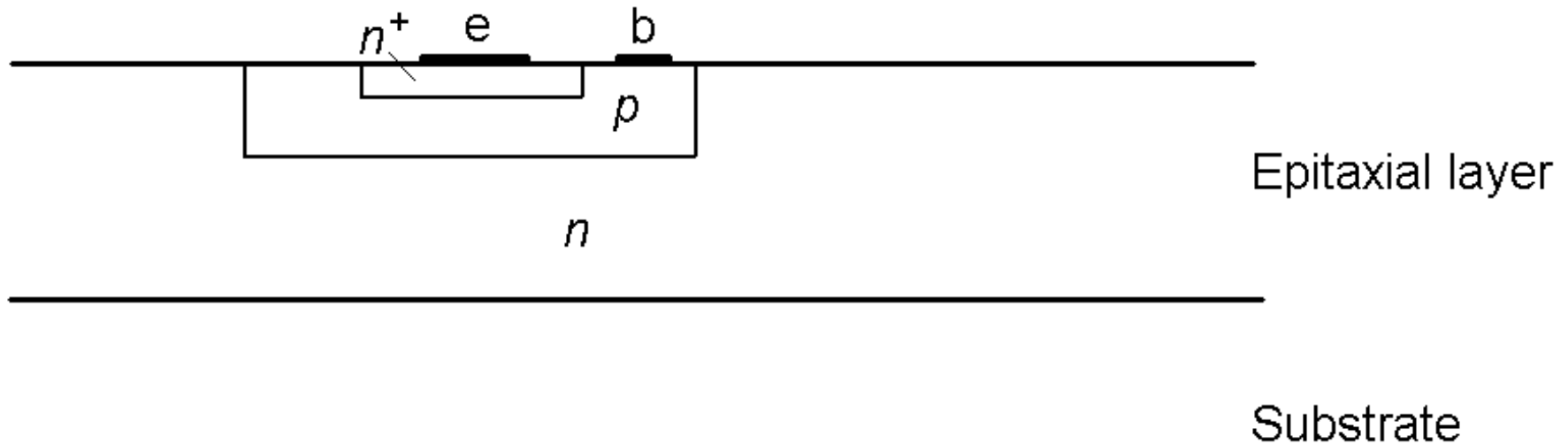
- The components are made as small and as close together as possible, because of size, speed and cost.
- The cost for processing, before the encapsulation step, is per wafer, not per device – the more dies the better.
- The yield, limited by local (point defects), is increased on the die level. There is less off-cutting and the relative area necessary for processing details is smaller (for example aligning marks).
- With defect density $\sim 0.1/\text{m}^2$, yield would be $> 99.8\%$. Other factors!

MOSFET Reduction



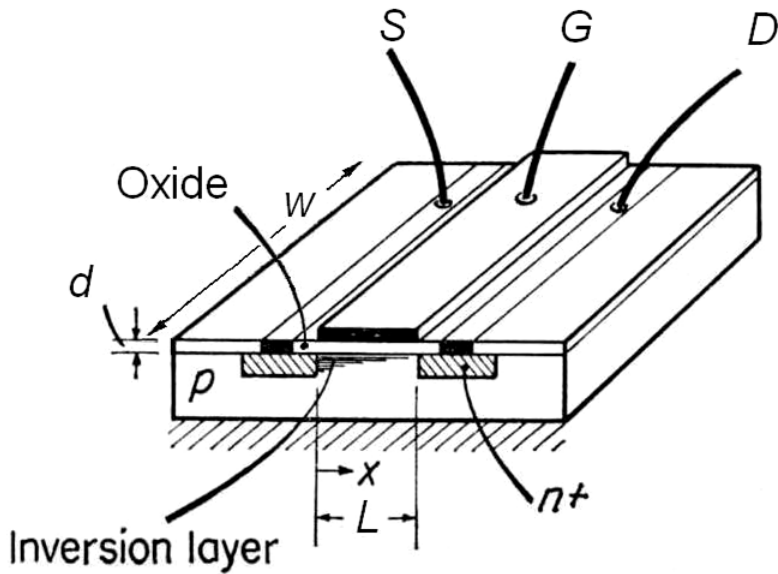
- Self-insulation is gives MOSFETs a major advantage in scaling.
- The gain in area (when compared to BJTs) is at least a factor of 5.
- The figure on the left is taken from Size and shows only the scaling until about year 2000.
- Nowadays is more customary to talk about gate lengths in nanometres.
- At short channel lengths, the gate control becomes critical and the structure effectively gains another $\frac{1}{2}$ dimension.
- The CMOS cells are also compact.

Bipolar Transistors in ICs



- The planar $n-p-n$ structure has already been discussed before.
- Metal interconnects can be deposited in one or more metallisation steps on the top surface (with some oxide or nitride insulation). Windows for contacting the individual transistors are readily opened by wet (say HF) or dry (say Ar ion) etching.
- Just doing the above, however is not sufficient. The circuit would be bound to fail. The BJTs must be insulated from one another!

MOSFETs in ICs – Self-Insulating

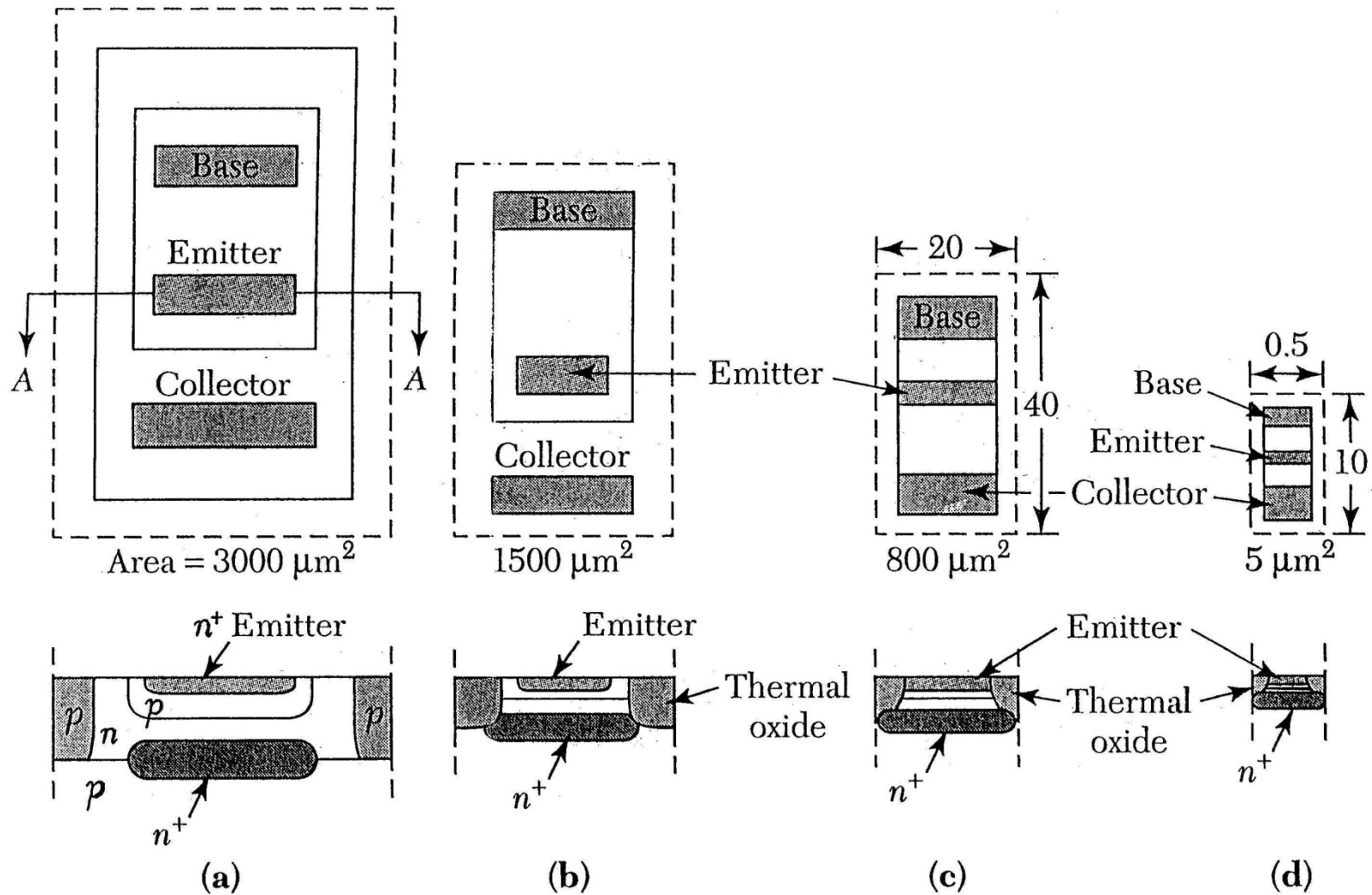


Construction of n -channel MOSFET

- All source, drain and channel are insulated by reverse-biased p - n junctions.
- The epitaxial layer is not highly doped for most applications.
- It is very important to observe correct biasing conditions.
- Area is saved (a few times), as there is no space wasted in insulation.
- The overall number of processing steps is lower.
- Smaller number of diffusions also means faster processing (the thermal treatment steps are the slow ones.)

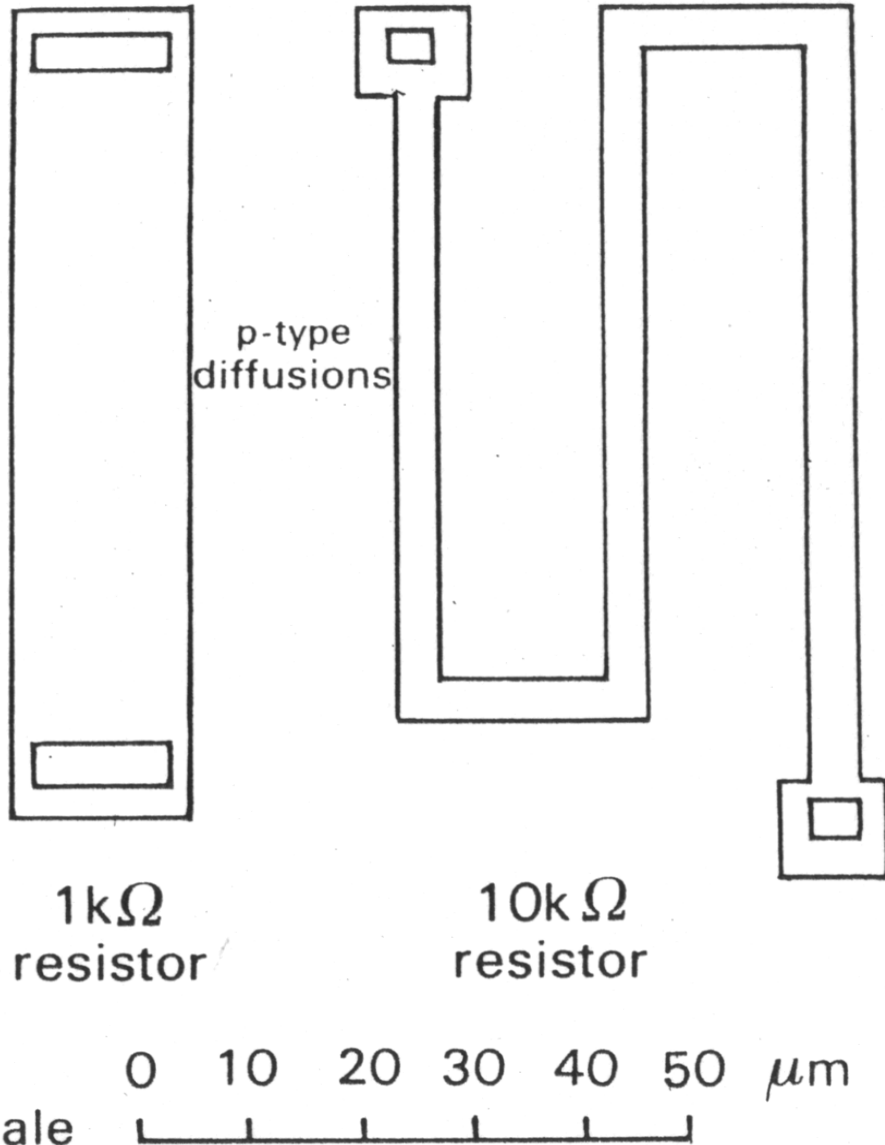
- All being well, parasitics are still to be controlled.
- Certain advantages to be gained by going to SOS and SOI technologies.

Bipolar Integrated Transistor - Size



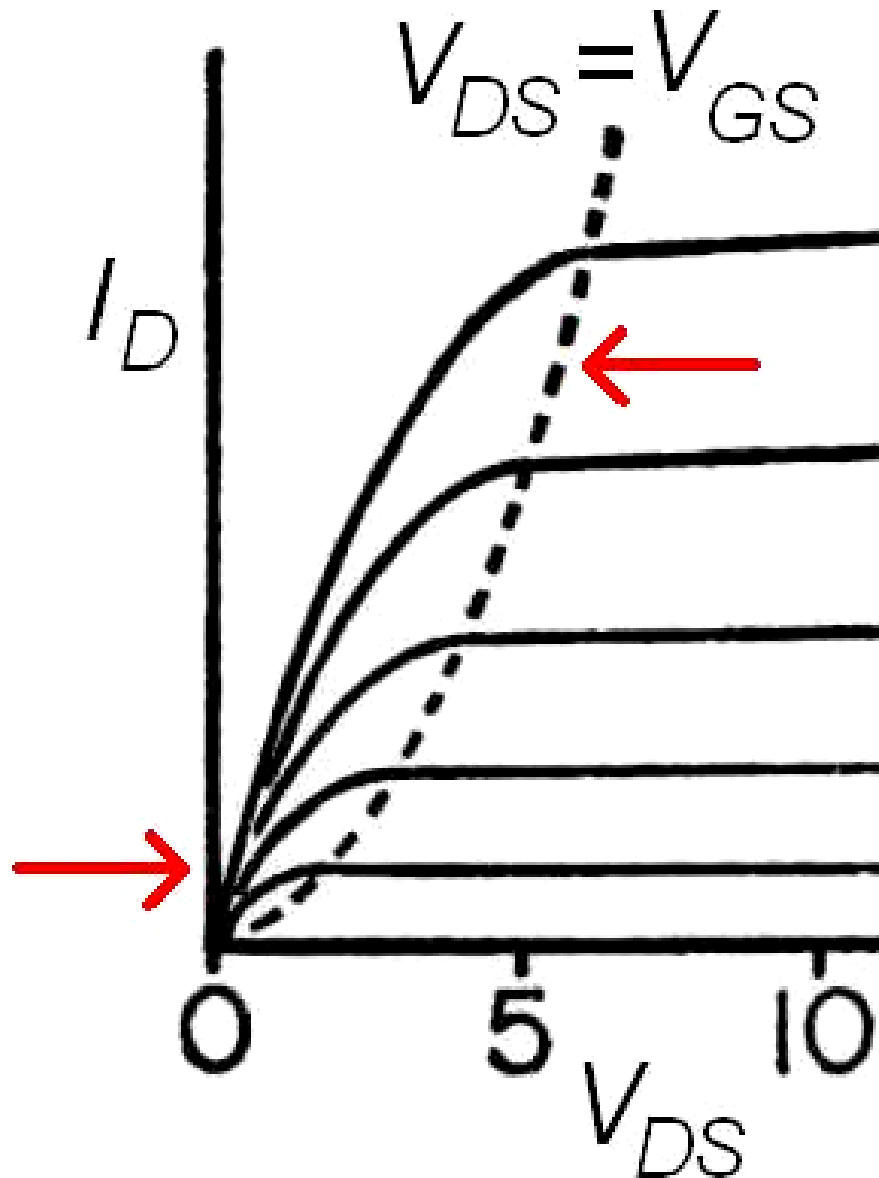
Reduction of the horizontal and vertical dimensions of a bipolar transistor. (a) Junction isolation. (b) Oxide isolation. (c) and (d) Scaled oxide isolation.

Passive Components in ICs



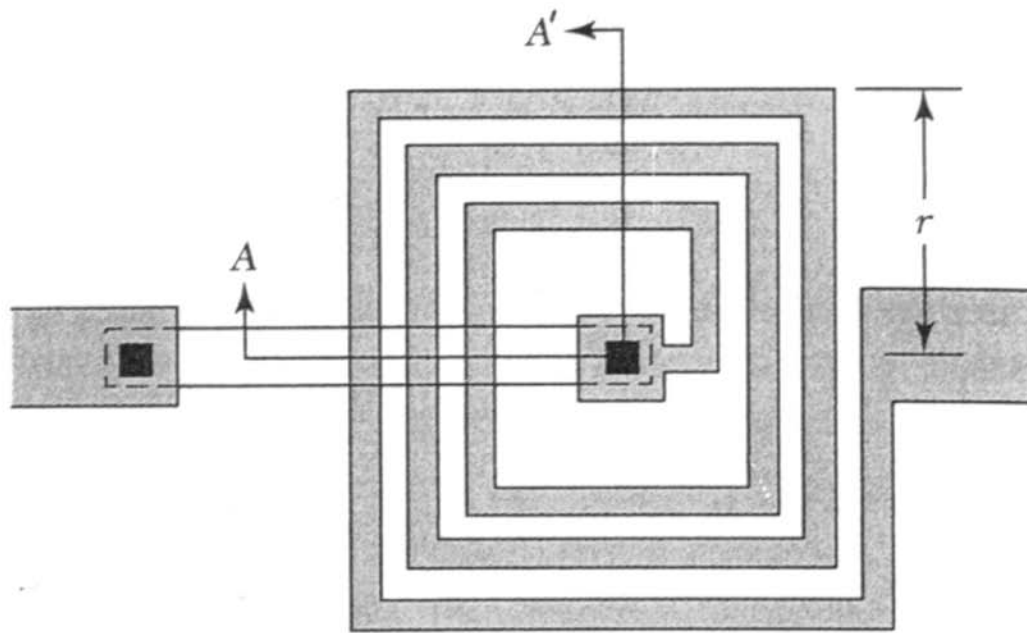
- Possible but not very common.
- Essentially thin wire resistor construction.
- Higher resistance with good control implies long meanders and therefore large area and cost.
- Precision doping control costs more and is slower.
- Cannot make the doping very low because of parasitics (like parasitic self-inductance) and because of carrier statistics noise.
- There are other options.

MOSFETs as Passive Components

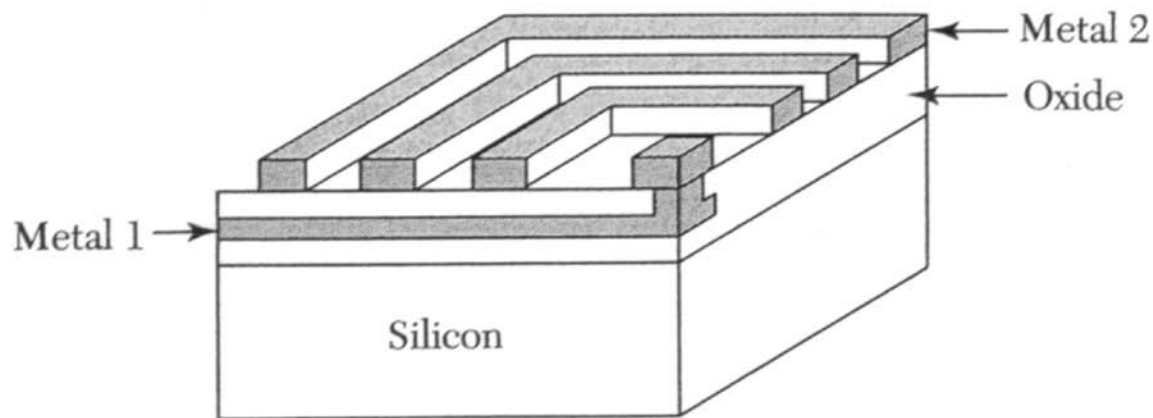


- Operation is possible either by setting an predefined gate bias (constant) or by simply shorting drain to gate.
- Operation at pinch-off is a rather common configuration.
- The motto becomes – make every component out of transistors and then create only transistors on the chip.
- Even tuneable capacitors are possible (varicaps) by utilizing reverse-biased $p-n$ or Schottky junctions.
- Gate MOS structure possible.

IC Inductors



(a)



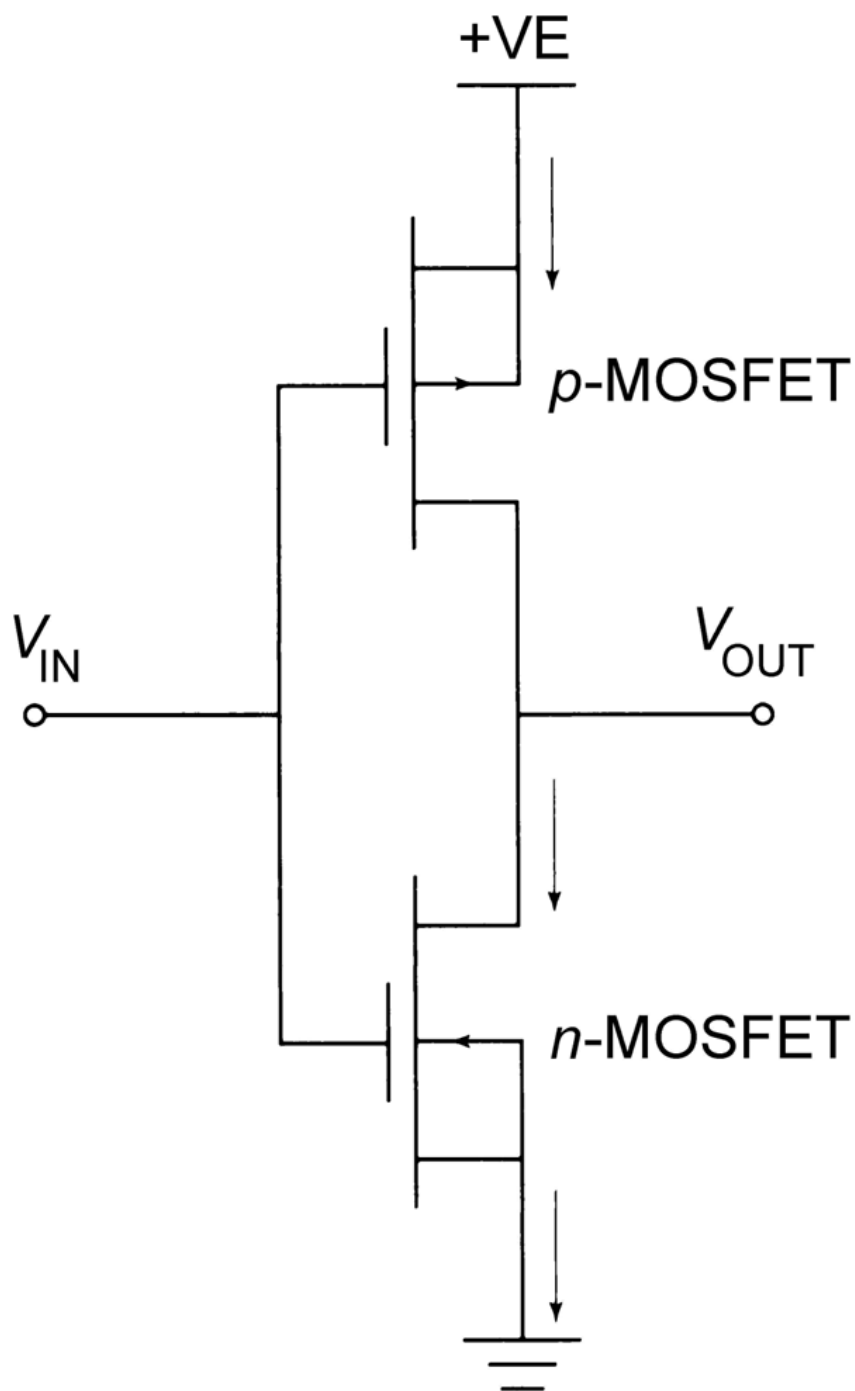
(b)

- Expensive and uncommon.
- Used primarily in high-frequency circuits because of size advantages – linear scaling.
- Used as insulation transformers in power supply circuits and as data transformers in isolating amplifiers.
- Nonlinear inductors (mostly permalloy-based are also used).

Modern ICs Design Rules

- Use few or no passives, at all. They are expensive, difficult to control and can be simulated by transistors.
- Digital electronics can be done with no passives, whatsoever.
- Maximize the number active elements and unify the masking patterns. Even diodes are often transistors on a chip.
- If something can be done in a digital way – do it in a digital way (even if it takes more elements to achieve).
- If more power is needed – again – use more transistors.
- There are a number of advantages to Digital Signal Processing (DSP) and digital-to-analogue (DAC) and analogue-to-digital (ADC) converters are quickly getting cheaper and faster.
- Even power analogue output amplifiers can be realized by using digital electronics strategies and cheap bulk-element filters (that would be used anyway).

The CMOS Inverter



- CMOS as a major factor for the proliferation of MOSFETs in ICs.
- The example of a simple logic element - NOT gate (on the left.)
- Draws virtually no current when stationary.
- Good for making memory – battery-supported CMOS is still very widely used.
- Made the portable electronic watch and small game consoles possible.
- Nowadays has rather low charging capacitance.
- Definitely a circuit to remember!

Thanks and Acknowledgements



Thank You Very Much for Your Attention!