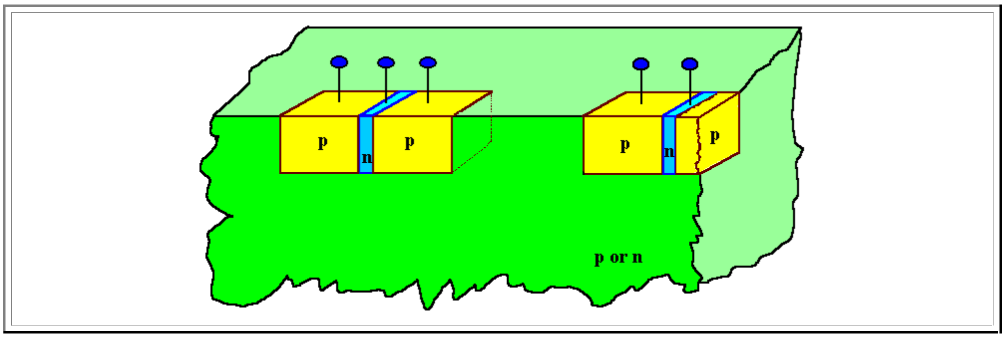
5.1.2 Basic Concepts of Integrating Bipolar Transistors

How *Not* to Make an Integrated Bipolar Transistor

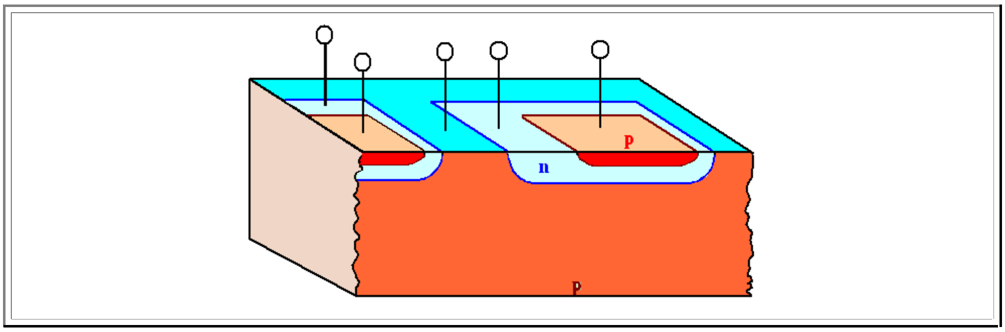
Obviously, embedding the three slices of Si that form a bipolar transistor into a **Si** crystal will not do you any good **-** we just look at it here to see just how ludicrous this idea would be:



What is the problem with this approach? Many points

- The transistors would not be insulated. The **Si** substrate with a certain kind of doping (either **n**- or **p**-type) would simple short-circuit all transistor parts with the same kind of doping.
- There is not enough place to "put a wire down", i.e. attach the **leads**. After all, the base width should be very small, far less than **1 µm** if possible. How do you attach a wire to that?
- How would you put the sequence of **npn** or **pnp** in a piece of **Si** crystal? After all, you have to get the right amount of , e.g. **B**- and **P**-atoms at the right places.

So we have to work with the really small dimensions in ***z***-direction, into the **Si**. How about the following approach?



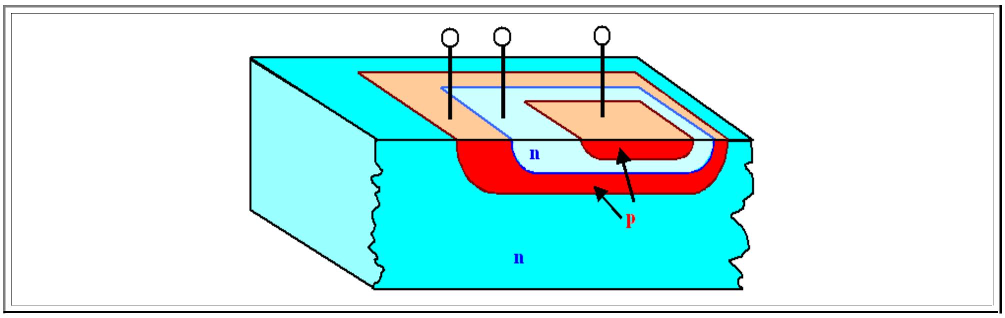
This is much better, but still not too convincing. The *pro* arguments are:

- Enough space for *leads*, because the lateral dimensions can be as large as you want them to be.
- It is relatively easy to produce the doping: Start with **p**-type **Si**, diffuse some **P** into the **Si** where you want the Base to be. As soon as you overcompensate the **B**, you will get **n**-type behavior. For making the emitter, diffuse lots of **B** into the crystal and you will convert it back to **p**-type.
- The base width can be very small (we see about this later).

But there is a major shortcoming:

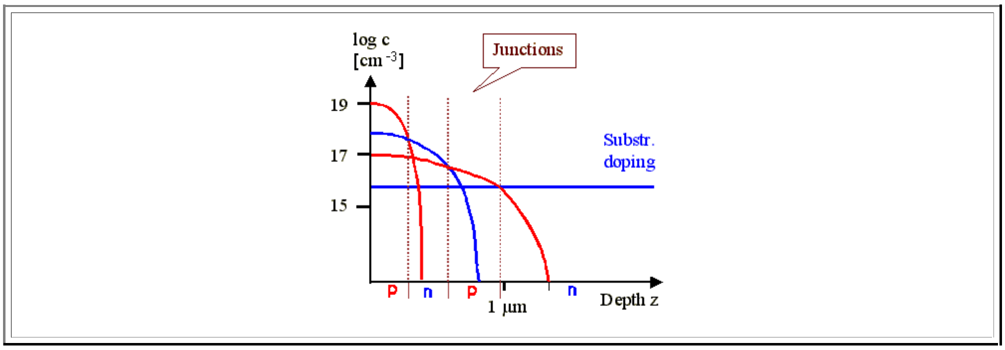
- Still *no insulation* between the collectors **-** in fact the **Si** crystal is the collector of all transistors and that is not going to be very useful.

Easy you say, lets add another layer of doped **Si**:



This would be fine in terms of insulation, because now there is always a **pn**-junction between two terminals of different transistors which is always blocked in one direction for all possible polarities.

- However, you now have to change an **n**-doped substrate to **p**-doping by over-compensating with, e.g. **B**, then back to **n**-type again, and once more back to **p**-type. Lets see, how that would look in a **diffusion profile** diagram:



The **lg** of the concentration of some doping element as shown in the illustration above is roughly what you must have - except that the depth scale in modern **ICs** would be somewhat smaller.

- It is obvious that it will be rather difficult to produce junctions with precisely determined depths. Control of the base width will not be easy.
- In addition, it will not be easy to achieve the required doping by over-compensating the doping already present three times. As you can see from the diagram, your only way in the resistivity is *down*. If the substrate, e.g., has a doping of **10 Ωcm**, the collector can only have a lower resistivity because the doping concentration must be larger than that of the substrate, so lets have **5 Ωcm**. That brings the base to perhaps **1 Ωcm** and the emitter to **0,1 Ωcm**. These are reasonable values, but your freedom in designing transistors is severely limited
- And don't forget: It is the relation between the doping level of the emitter and the base that determines the amplification factor γ

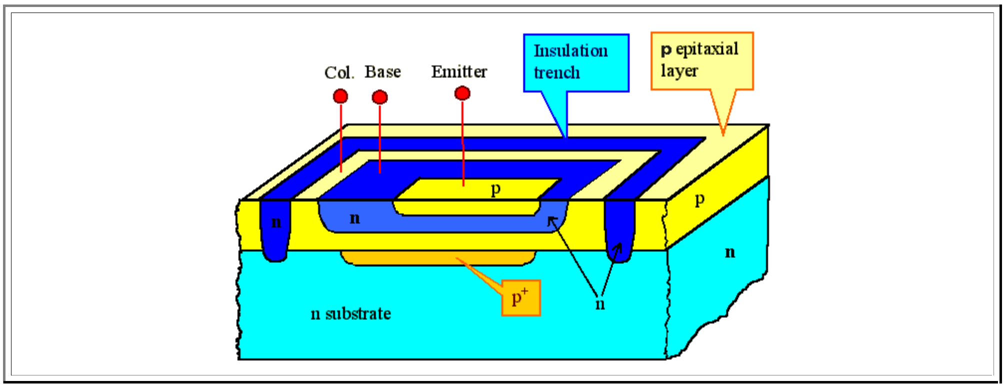
There must be *smarter* way to produce integrated bipolar transistors. There is, of course, but this little exercise served to make clear that integration is far from obvious and far from being easy. It needs *new ideas*, *new processes*, and *new materials* - and that has not changed from the first generation of integrated circuits with a few **100** transistors to the present state of the art with some **100** million transistors on one chip.

- And don't be deceived by the *low costs* of integrated circuits: Behind each new generation stands a huge effort of the "best and the brightest" - large scale integration is still the most ambitious technical undertaking of mankind today.

How to Make an Integrated Bipolar Transistor

So how is it done? *By inventing special processes*, first of all: **Epitaxy**, i.e. the deposition of thin layers of some material on a substrate of (usually, but not necessarily) the same kind, so that the lattice continues undisturbed.

- Lets look at a cross-section and see what *epitaxy* does and why it makes the production of **IC**s easier.



- We start with an **n**-doped wafer (of course you can start with a **p**-doped wafer, too; than everything is reversed) and diffuse the $\mathbf{p^+}$ layer into it. We will see what this is good for right away.
  - On top of this wafer we put an *epitaxial layer of **p**-doped Silicon*, an *epi-layer* as it is called for short. Epitaxial means that the crystal is just continued without change in orientation. The epitaxial layer will always be the collector of the transistor.
  - Next, we diffuse a closed ring of **n**-material around the area which defines the transistor deeply into the **Si**. It will insulate the transistors towards its neighbours because no matter what voltage polarity is used between the collectors of neighbouring transistors, one of the two **pn**-junctions is always in reverse; only a very small leakage current will flow.
  - Then we diffuse the **n**-base- and **p**-emitter region in the epi-layer.
- Looks complicated because it is complicated. But there are many advantages to this approach:
  - We only have *two "critical" diffusions*, where the precise doping concentration matters.
  - The transistor is in the epitaxial layer which, especially in the stone age of integration technology (about from **1970 - 1980**) had a much better quality in terms of crystal defects, level and homogeneity of doping, minority carrier lifetime τ, ...) than the **Si** substrate.
  - We get one level of wiring *for almost free*, the $\mathbf{p^+}$ layer below the transistor which can extend to somewhere else, contacting the collector of another transistor!
- This leads us to the next big problem in integration: The "wiring", or how do we connect transistors in the right way?