5.9.   Bipolar Power Devices

Power devices can be classified into bipolar-based devices, MOSFET-based devices and devices such as the IGBT that combine a bipolar transistor with a MOSFET.

Bipolar power devices are the traditional power devices because of their capability to provide high currents and high blocking voltages. The bipolar-based power devices include high-power bipolar transistors, Darlington transistors consisting of two transistors with a common collector, thyristors – also called silicon controlled rectifiers (SRCs) and triacs, a complementary thyristor structure suitable to control AC power.

Power MOSFETs and power devices that combine MOSFETs and bipolar transistors are covered in chapter 7.

5.9.1. Power BJTs

High power bipolar transistors are conceptually the same as the bipolar transistors described in chapter 8. The main difference is that the active area of the device is distinctly higher, resulting in a much higher current handling capability. Power BJTs also have a thick and low-doped collector region. Such collector regions result in a large blocking voltage. Extremely low doping densities, down to 10^{13} cm^{-3}, are use to obtain blocking voltages as large as x000 V. As a result, one finds that the structure needs to be redesigned to a) effectively manage the power dissipation and b) avoid the Kirk effect.

The power dissipation is managed by minimizing the power dissipation and spreading the resulting heat dissipation onto a large area. The Kirk effect is normally avoided by increasing the collector doping density. However, for devices with a very high blocking voltage, this may not be an option. Power BJTs therefore are operated at rather low current density of 100 A/cm^2 since the lower current density reduces the power dissipation per unit area and eliminates the Kirk effect. Large currents – up to 1000 A – are obtained by making a large area device. Silicon BJTs dominate the power device market, in part because of the low cost of large area silicon devices and the high thermal conductivity of silicon compared to GaAs. Silicon carbide (SiC) has been hailed as the perfect material for high-power BJTs. The higher thermal conductivity (3x) and breakdown field (10x) compared to silicon give it a clear performance advantage. The high saturation velocity (3x compared to silicon) also shifts the onset of the Kirk effect to higher current densities. The proliferation of its use will heavily depend on the material cost and quality of the SiC wafers.

5.9.2. Darlington Transistors

Darlington transistors contain two transistors connected in an emitter-follower configuration, while sharing the same collector contact. This structure can be fabricated with the same technology as a single BJT as shown in Figure 5.9.1. The key advantage of the Darlington configuration is that the total current gain of the circuit equals the product of the current gain of the two devices. The disadvantage is the larger saturation voltage. Since the two devices share the same collector, the saturation voltage of the Darlington pair equals the forward bias voltage of transistor Q2 plus the saturation voltage of transistor Q1. Since the forward bias voltage is much larger than the saturation voltage, the saturation voltage of the Darlington pair is also significantly larger. This larger voltage results in a larger on-state power dissipation in the device.
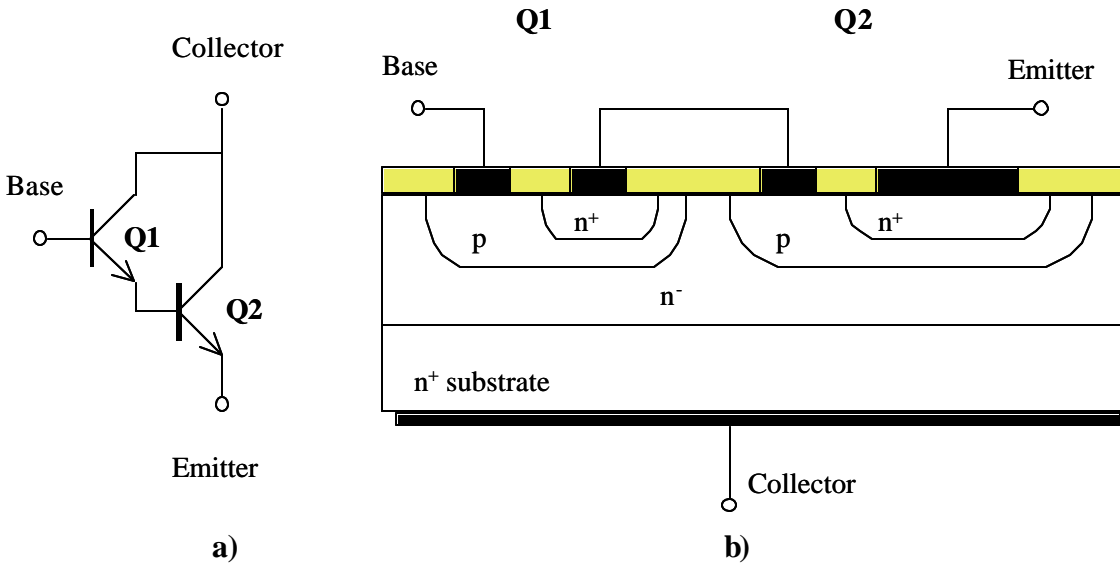
Figure 5.9.1. Darlington transistor structure a) equivalent circuit b) device crosssection.

5.9.3. Silicon Controlled Rectifier (SRC) or Thyristor

The silicon controlled rectifier is 4-layer device with alternating n-type and p-type layers as shown in Figure 5.9.2. This devices is also referred to as a pnpn structure or Thyristor. Such device can in principle be made using any semiconductor. However, silicon thyristors are the most common thyristors. The advantage of the structure is that it provides a high power handling capability, high blocking voltage and high gain with a very low on-state resistance.

The operation of the device is best explained by considering the equivalent circuit, shown in Figure 5.9.2. It consists of two bipolar transistors, a n-p-n transistors, Q1, and a p-n-p transistor, Q2. Both transistors share a p-type and n-type layer. For instance, the p-type base layer of transistor Q1 is also the collector layer of transistor Q2, while the n-type base of transistor Q2 is also the collector of transistor Q1. The Thyristor is controlled by the gate electrode, which is the gate of Q1. By applying a current to the gate one forward biases the base-emitter junction of Q1, which leads to a collector current in Q1, which in turn provides a base current to Q2. Since Q2 is a complementary p-n-p transistor, this negative current also forward biases the base-emitter junction of transistor Q2, resulting in collector current which forms an additional base current into the base of transistor Q1. The applied current to the gate of the Thyristor therefore causes an additional current into Q1, which can be large enough that both transistors remain in turned on even if the original gate current is removed. This latching behavior is not unlike that of a flip-flop, where the inputs of two devices are connected to the output as shown in Figxxx. This self-sustaining effect will occur if the product of the current gain of both transistors equals unity, while one of the transistors can have a current gain less than unity. As a result one has considerable flexibility to choose the doping density and thickness of each of the layers to obtain a high blocking voltage and high Early voltage for each transistor, while maintaining sufficient current gain.

The Thyristor has a lower on-state voltage than the Darlington pair and typically requires an

even smaller turn-on current, which only needs to be applied temporarily because of the internal positive feedback between the two transistors of the equivalent circuit.

This latter property is also the main disadvantage of the Thyristor: since the device latches into the on-state once sufficient gate current is supplied, the device can not be turned off by removing the gate current. Instead one has to disconnect the power supply to turn off the device. Furthermore, since both transistors are in saturtion in the on-state, a significant amount of minority carriers are accumulated in the base region of each transistor. These minority carriers must be remove prior to reconnecting the power supply since these carriers would temporarily lead to a base current in each device and trigger the turn-o of the Thyristor. Finally, one has to slowly ramp up the power supply voltage to avoid the so-called dV/dt effect. Since a rapid increase of the applied voltage with time causes a displacement current proportional to the capacitance of the junctions, this displacement current could again provide a temporary base current in Q1 and Q2, which is large enough to trigger the Thyristor.
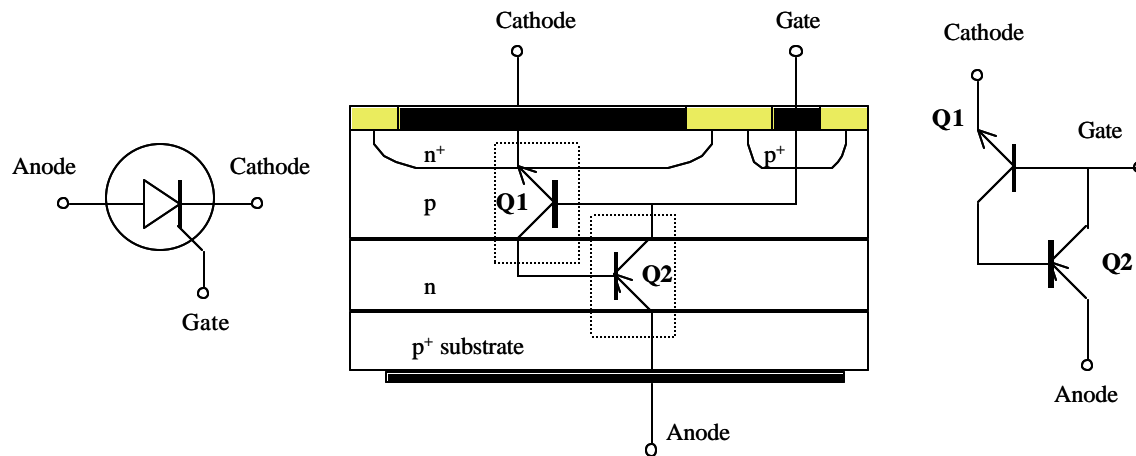

Figure 5.9.2. Thyristor structure: a) circuit symbol, b) device cross-section and c) equivalent circuit.

A very attractive feature of a Thyristor is that it can be scaled easily to very large area devices even if that causes a significant lateral resistance though the thin and lowly-doped base and collector regions. As one applies a current to the gate electrode, the Thyristor would be triggered locally. The turned-on region would then spread laterally thoughout the structure without a need for an additional gate current. The local triggering also exists in the light-controlled Thyristor. This structure does not contain a gate electrode. Instead the p-n-p-n structure is locally illuminated with photons whose energy exceeds the bandgap energy of the semiconductor. The photogenerated current then acts as the gate current, which triggers the Thyristor.

Gate turn-off Thyristor (GTO)

5.9.4. DIode and TRiode AC Switch (DIAC and TRIAC)

The diode AC switch and the triode AC switch are very similar to the thyristors, since they both are latching multi-layer device structures. Both are meant to be used in AC powered systems and therefore respond similarly to positive and negative applied voltages. The circuit symbols and layer structures are shown for both devices in Figure 5.9.3. The diode AC switch also referred to

as DIAC consists of a gate-less pnpn structure connected in parallel to a gate-less npnp structure. This device therefore acts like an open circuit until the threshold voltage is reached - either positive or negative – after which the device acts as a short. To achieve this function one starts with a pnp structure. An n^+ region is added to the front and the back to yield the DIAC structure.

The triode AC switch (TRIAC) also contains the same vertical structure as a DIAC. In addition a contact is made to the p-type gate of the npnp structure as well as the n-type gate of the pnpn structure. This additional gate contact allows lowering the threshold for latching for both positive and negative applied voltages applied between terminal 1 and terminal 2.
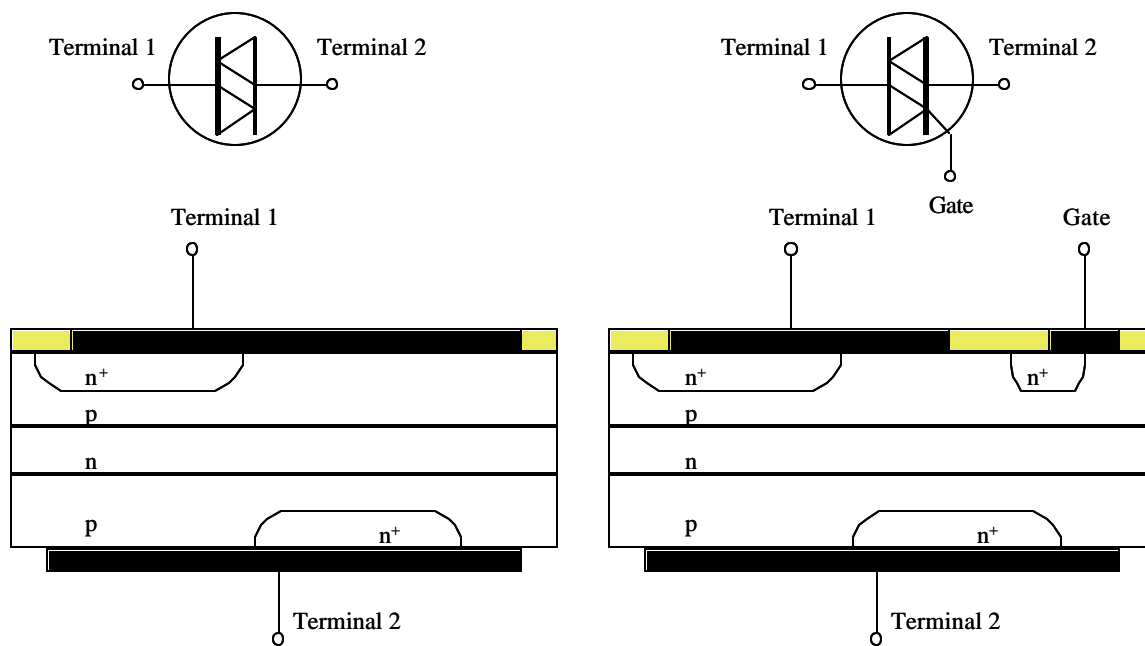
Figure 5.9.3. Circuit symbol and device cross-section of a) a Diode AC switch (DIAC) and b) a Triode AC switch (TRIAC).