Semiconductor Technology from A to Z

Metallization

Aluminum technology

Aluminum and aluminum alloys

Aluminum and its alloys were the standard material for on-chip wiring for decades and continue to be used wherever the smallest structures are not critical: for bond pads, in power and analog technology, and on non-critical upper layers. Aluminum offers:

- good adhesion to SiO_2 and interlayer dielectrics such as BPSG and PSG,
- good contactability when wiring to the package (e.g. with gold and aluminum wires),
- a low resistivity of 2.7 µΩ·cm for pure aluminum, and about 3 µΩ·cm for the common alloys with silicon and copper,
- and it can be patterned very well by dry etching.

The last point was long a decisive advantage: aluminum forms volatile compounds with chlorine and can therefore be deposited over the full area like any other layer, masked with resist, and etched. This simple process is precisely what is not available for copper.

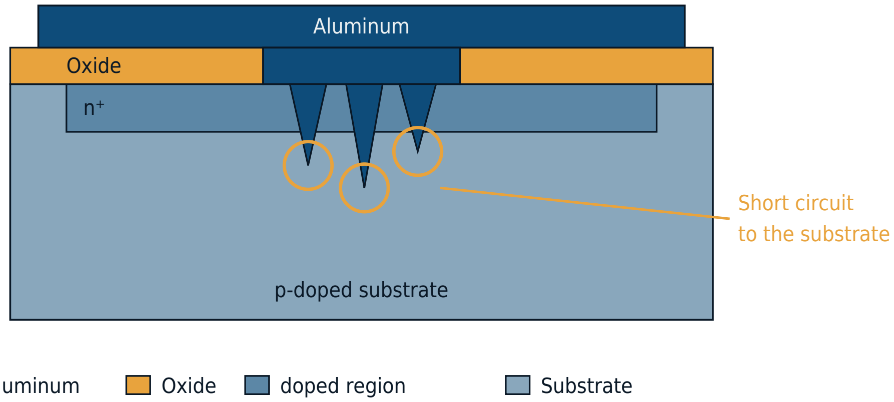
However, aluminum meets the requirements for electrical load capacity and corrosion resistance only partially. The following sections describe the three effects at which aluminum technology reaches its limits: the diffusion of silicon into the metal, electromigration, and the growth of hillocks. Metals such as silver or copper are considerably better in this respect, but cannot be dry-etched – for these, a different patterning process first had to be found.

Diffusion in silicon

The use of pure aluminum can lead to a diffusion of silicon atoms into the metal. Silicon dissolves into solid aluminum well below its melting point; at the usual sintering temperatures of 400–450 °C, which are used to improve the contact after the metal has been deposited, this occurs to a considerable extent. The semiconductor reacts with the aluminum metallization, and the resulting material loss, caused by the outdiffused atoms, leaves pits at the contact area between silicon and aluminum. The aluminum fills these pits. This creates "spikes," which can, under certain circumstances, lead to short circuits if they extend through the doped regions into the silicon crystal.

Spike Formation

The aluminum spikes pierce through the doped region

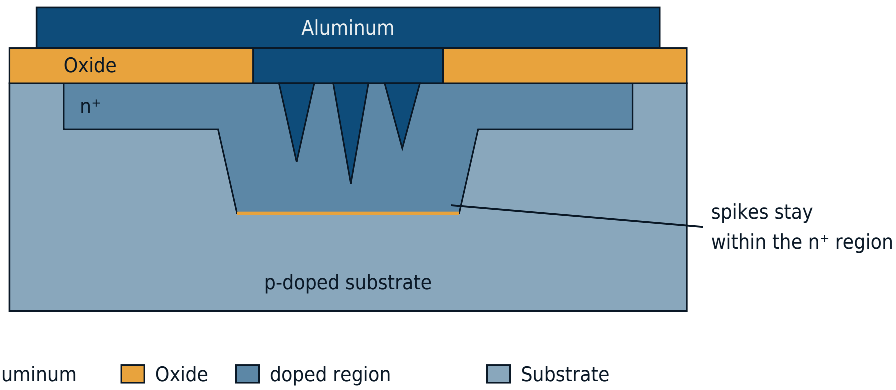


During sintering, silicon dissolves into the aluminum, leaving pits that the metal fills in. If the spikes reach deeper than the doped region, the junction is short-circuited.

The size of these spikes depends on the temperature at which the aluminum is deposited onto the silicon. There are several ways to prevent these spikes. At the location of the contact hole, a deep ion implantation, the contact implantation, can be introduced. This ensures that the spikes do not extend into the substrate.

Contact Implantation

The more deeply doped region catches the spikes



The deep implant beneath the contact hole moves the junction further down. It costs an additional process step and changes the electrical properties of the region.

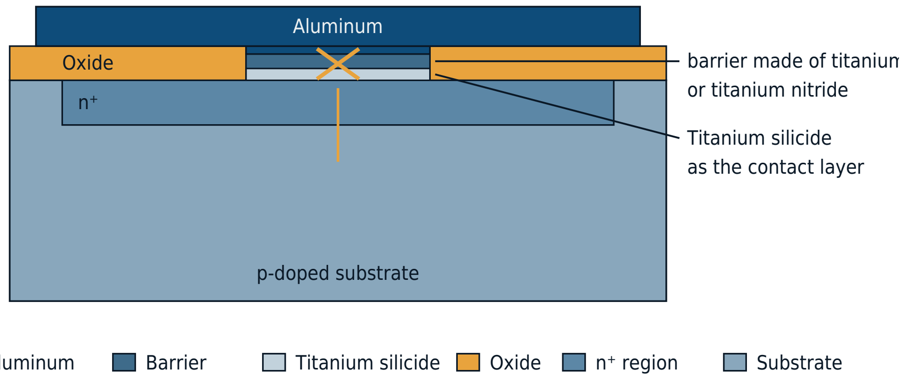
The disadvantage, however, is that an additional process step has to be introduced, and the electrical properties change due to the enlargement of the doped region.

Instead of pure aluminum, an aluminum-silicon alloy containing about 1–2 % silicon can also be used. The aluminum is now already mixed with silicon, and silicon atoms no longer diffuse out of the wafer into the aluminum. With very small contact holes, however, silicon can precipitate at the contact area, resulting in an increased contact resistance.

For high-quality contacts, a separation between aluminum and silicon is required. For this purpose, a barrier of various materials, such as titanium, titanium nitride, or tungsten, is deposited on the silicon. To prevent an increase in contact resistance at the interface between titanium and silicon, a contact layer of titanium silicide must also be applied here.

Barrier Layer Between Aluminum and Substrate

Aluminum and silicon no longer touch



The blocked arrow represents the suppressed diffusion: the barrier holds back the silicon, and the silicide keeps the contact resistance low. Without this interlayer, the transition from titanium to silicon would be too high-resistance.

This barrier is the forerunner of what became standard practice in copper technology: there, a diffusion barrier surrounds every single interconnect. Spike formation itself is thus a historical problem – today, the contact to the silicon is made via a silicide and a tungsten, cobalt, or ruthenium plug, and aluminum no longer touches the silicon at all.

Electromigration

At high current densities (current flow per area), the flowing electrons transfer a small amount of momentum to the ion cores with every collision. Individually, this impulse is insignificant, but in total this "electron wind" slowly pushes the atoms out of their positions in the direction of current flow. Especially at locations with a small interconnect cross-section, the current density is increased; as the atoms shift, the cross-section decreases further, and the current density rises even more. Such constrictions are found in particular at edges over which the interconnects run. In extreme cases, the aluminum interconnects break due to this material transport.

Damage to interconnects caused by electromigration

(Source: Max-Planck-Institut für Metallforschung Stuttgart)

Electromigration limits how much current an interconnect can carry continuously. Since the cross-section decreases with every shrink, but the current to be switched does not decrease to the same extent, this has tended to become more important over the years. Copper withstands roughly a hundred times the lifetime of aluminum under the same load, because its atoms are more strongly bound. In this case, the material transport shifts to the interfaces: copper atoms migrate preferentially along the top of the interconnect, where it borders the capping layer. A thin cobalt layer on the interconnect, instead of a purely dielectric cap, binds the surface and significantly extends the lifetime.

Hillocks

Electromigration causes material to be shifted and accumulated at locations of lower current density. These so-called hillocks can break through overlying layers and thus cause a short circuit with another metallization layer; in addition, moisture can penetrate through the resulting cracks and lead to corrosion. Hillocks can, however, also arise due to differing coefficients of thermal expansion of the materials. The materials expand differently with temperature changes, creating stresses between the layers. This problem can be solved using compensating layers that have an "intermediate" coefficient of expansion (e.g. titanium, titanium nitride).

Further negative effects that can occur during metallization:

- Stray exposure: due to unevenness, incident light rays during exposure can be reflected in such a way that areas are exposed uncontrollably. Reflection is prevented with the help of an anti-reflective coating (ARC); on metal this is usually titanium nitride, while on other layers silicon oxynitride or an organic resist is used
- Poor edge coverage: at edges, increased layer growth can occur, while at corners growth is reduced. To counteract this, edges can be rounded before metal deposition:

The design of the interconnects therefore has to be planned precisely to prevent these problems. By adding a small amount of copper, the lifetime of aluminum interconnects can be substantially increased, although patterning of aluminum mixed with copper becomes considerably more difficult. To protect against corrosion, the surfaces are passivated with silicon dioxide or silicon nitride. This passivation is the actual protection: the vast majority of devices are encapsulated in plastic. Ceramic packages remain reserved for applications that must be hermetically sealed, such as in aerospace. How metallization layers are deposited onto the wafer is described in more detail in the chapter Deposition.