The Advantages of Integrated Passives

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Market demand for higher performance and more compact electronic products (mobile phones, PDAs, digital cameras, etc.) is behind the integration of passive components such as resistors, inductors, and capacitors. Especially the requirement for high-frequency signal handling and the integration of optical signals into electronic packages are a major driving force for the integration of passives into various devices.

Because of their advantage in performance, size and assembly cost, integrated passive devices (IPDs) are yet another booming area of advanced packaging. Many of today's electronic products feature 500 or more passive devices, making conventional packages and board assemblies a problem in terms of performance, yield and cost. IPDs typically combine a number of passive components (resistors, capacitors, and inductors) in a single package. These devices are increasingly built on glass thin film substrates rather than on silicon-like semiconductor devices or ceramic which is very high in cost. The IPD is ideally combined with wafer level packaging – yielding minimal size and low costs, since there is no longer a need for a conventional plastic package.

Another way to integrate passives is to build them right into the high-density substrates – as integrated passive modules (IPMs). While the process technology is identical to IPD, the integration of the passives into the substrate has the advantage that no extra space is needed for the passives and the assembly step of the devices is eliminated. This technology is ideal for products such as mobile phones with their high volume and the need for small size and low cost.

Yet another method for passive device integration in the early stages is to combine them on the wafer level together with the wafer level packaging steps. By establishing multiple metal/passivation layers (up to 5), the passive components are built directly onto the die between the chip and the first level interconnect, which is typically a solder bump.

The methods to produce precise resistors, capacitors, and inductors on wafers or substrates usually involve thin film technology for most of the applications. Resistors are preferably made by sputtering of TaN, NiCr – including its ternary alloys – and SiCr through a lift-off type photo resist. Inductors are sputtered in the shape of a plating base and then enforced by an electroplating step to increase the cross section of the trace. Alternatively, they are sputtered over the full thickness and etched by subtractive etch technology, the latter being suitable only for ratios of thickness to line width below 0.25.

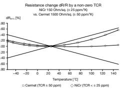
Multiple choices are available to create capacitors. Depending on the requirements, sputtering can be efficiently done for Al_2O_3, AlN, SiO_2, Si_3N_4, Ta_2O_5, TiO_2, and some more dielectrics. Because of the relative low sputter rates of dielectric films, PECVD techniques are preferred for the thickness range above 2.0 to 3.0 µm. Spin-on of high k dielectrics is used as a low cost alternative.

Sputtering

Cathodic sputter deposition is the most versatile solution for the production of electronic circuits. Although the starting pressure should be better than 2×10^{-8} mbar to avoid contamination, sputtering takes place in a low-pressure atmosphere of inert gas, such as argon, in the range of 10^{-3} mbar.

A glow discharge is formed by applying a high voltage (approx. 200 V–2000 V) between anode and cathode, which is formed by the material to be sputtered (diode sputtering). An electron source supports ionization of the inert gas, and the positively charged argon ions are accelerated towards the cathode (triode sputtering). These ions bombard the cathode material (target) with high energy and force atoms and molecules to break away from the cathode by virtue of their kinetic energy. Some of these sputtered particulates are intercepted by the substrate and form a uniform thin film layer. Adding magnets nearby the target increases the travel-distance of the electrons, thus increasing the probability of collision with argon molecules (magnetron mode). This way high deposition rates can be managed at low pressure. To improve the film uniformity

Figure 1: Resistance change due to non-zero TCR



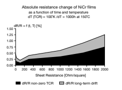


Figure 2: Resistance change as a function of time and temperature

across the substrate, either the substrates are rotated relative to the cathode (batch type with rotating drum), or the magnetic field rotates behind the target (often used with single wafer solutions). Very tight tolerances of film thickness < ± 2 % across a 200 mm wafer can be realized.

Sputtering offers the highly interesting possibility to change the chemical composition of the deposited film by applying reactive gases such as oxygen or nitrogen to the inert gas atmosphere. The properties of the deposited film can be altered depending on the concentration of the added reactive gas.

This process is called reactive sputtering and is used frequently to

- Produce resistor films like Ta_2N
- Control the TCR of NiCr films
- Stuff barriers such as TiN or TiW(N)
- Form insulating layers like Si_3N_4 or Ta_2O_5

When increasing the flow rate of the reactive gas, the metal sputtering mode with a high deposition rate due to a metallic non-contaminated target, has to be distinguished from the compound mode, where with increasing reactive gas flow, reactive products are also formed at the target surface, causing the deposition rate to slow down. Slightly doped NiCr resistors and Ta_2N films are sputtered in the metallic mode, whereas insulating layers will utilize the compound mode. To keep such processes stable, a pulsed DC power supply may be helpful. If the deposition should take place in the transient region between metallic and compound mode, a process control can be installed, which maintains the gas flow by mass spectrometry (RGA) and the metal rate by optical emission spectrometry (OES). If the substrate already is an insulating material, then an RF plasma system – usually operating at 13.56 MHz – is the appropriate solution. Sputtering can occur, because the target is bombarded in the RF-field with ions and electrons alternatively.

Heating the substrates before or during the deposition will influence the mobility of the incoming molecules and atoms and thus control gas incorporation. The deposition temperature influences film parameters such as stress, adhesion, density, and resistance. Similar effects can be achieved by applying DC- or RF-substrate bias. Controllable substrate heaters and coolers with an optional substrate bias are available with state-of-the-art sputter systems such as LLS EVO or CLUSTERLINE®.

Thin films for integrated passive applications

Important applications of integrated passives:

- Clock terminators and filter networks used in CPUs such as INTEL's Pentium
- EMI filters and ESD protectors
- Zero Ohm jumper arrays
- Bus terminators such as serial/parallel termination array networks and AC termination networks
- Precision resistor arrays, such as isolated and bussed resistor networks, voltage divider networks, and audio resistor arrays

All these applications contain a more or less large amount of resistors, capacitors, and inductors. High-quality requirements, especially for resistor films, lead to sputter-deposited thin film solutions.

Resistors

Most important for the practical use of resistors in IP circuits is the capability to sustain a certain nominal resistance value over the entire time of use.

A non-zero temperature coefficient of resistance (TCR) leads to a resistance change as a function of variable operating temperatures *(Figure 1)*, while a long-term drift of the film material leads to a resistance change as a function of time. *Figure 2* shows the superposition of both effects for a sheet resistance range from 2 Ohm/square to 2'000 Ohm/square. For this example, a temperature change

Figure 5: Interconnect wiring with integrated passive devices

of 100°K during operation and storage for 1'000 hours at 150°C was assumed. The most stable region is between 50 Ohm/square to 200 Ohm/square.

Sophisticated sputter techniques like reactive sputtering and sputtering of ternary alloys are the key for NiCr- and Tantalum-based films with high stability and low TCR over a wide range of sheet resistance values, e.g. from 2 to 2'000 Ohm/square. Furthermore, sputtered thin films exhibit a superior performance with respect to noise level, even in the GHz frequency range.

NiCr films cover an especially wide range of applications. Standard NiCr films, reactively sputtered from a compound target in an oxygen atmosphere, are available with a sheet resistance up to 300 Ohm/square, a TCR below ± 25 ppm/°K and a long-term stability of about 0.1% deviation from the nominal value after 1'000 hours storage at 150°C.

Resistor films for high-frequency applications adhere well to highly polished glass, quartz, sapphire or AlN substrates. Dissipation by magnetic materials should be avoided. NiCr films with very low Ni content, reactively sputtered in a nitrogen atmosphere, will match those requirements.

Sputtering of ternary alloys such as NiCrAl provide a TCR below ± 10 ppm/°K and a long-term stability better than 0.03% after 1'000 hours at 150°C. Cermet films such as TaSi are used for higher sheet resistance requirements.

Cermets are suitable materials when higher sheet resistance values are required. Compound targets, co-sputtering and reactive sputtering are techniques to realize a semicontinuous conductive phase with an appropriate composition of dielectric and conductive components. TCR values below 200 ppm/°K and a sheet resistance up to 2'000 Ohm/square have been achieved with combinations of NiCr and SiO_2 or Al_2O_3. If TCR requirements are not so stringent, SiCr is a proven cermet material. Long-term stability is comparable to standard NiCr films.

Ta-based thin films are an attractive alternative to the NiCr films above. In addition to its refractory nature, which implies that any imperfection frozen in during deposition will not anneal out during lifetime, tantalum belongs to a class of metals known as valve metals, which form tough self-protective oxides, either through anodic oxidation or through heat treatment in an oxygen atmosphere. Since tantalum is such a reactive material, the sputtered films have a tendency to be contaminated during deposition.

A controlled contamination is desirable to achieve useful properties. The most common process is reactive sputtering in a nitrogen atmosphere to form Ta_xN films. By increasing the N_2 flow the resistance rises and levels out at ~ 200 to 250 µOhm · cm, whereas the TCR drops down from positive values and stays at ~ –100 ppm/°K. The composition of these "plateau" films is very close to Ta_2N and displays the greatest stability during load-life tests.

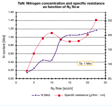


Figure 3: Specific resistance of TaN obtained on the CLUSTERLINE®.

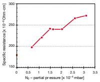


Figure 4: Specific resistance of TaN obtained on LLS EVO

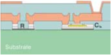


Figure 6: Multilayer metallization scheme with integrated thin film resistors (R) and capacitors (C)

To reach a stable final value, Ta_2N films need a thermal post-treatment just like NiCr films. A good indicator for plateau films is the fact that the TCR is only negligibly changed during this heat treatment, whereas the resistance value rises, depending on time and temperature. The sheet resistance increases because during heat treatment the surface of the Ta_2N film is changed to self-protective oxide and the electrical effective thickness of the Ta_2N layer decreases. This effect may be used for thermal trimming of the resistors without any laser cut, which is an important fact for very-high-frequency applications.

The common sheet resistance range for Ta_2N films is 30 to 300 Ohm/square with a TCR between –70 to –130 ppm/°K. Long-term stability is better tan 0.05% after 1'000 hours at 150°C.

High-conductive films for interconnect wiring

In high-density and high-frequency applications combined with integrated passives, aluminum or copper rewiring is used instead of the more expensive gold, which was typically used in former hybrid applications. The thickness range of these layers is between 0.5 µm and 5.0 µm, thin enough to be sputtered within a reasonable amount of time with modern planar magnetron technology. Adhesion promoters such as Chrome or Titanium, and barrier layers such as Nickel, Titanium-Tungsten or Titanium Nitride will help to improve temperature stability of the circuit and reduce diffusion, migration, and segregation of contact material into the resistance layers and vice versa.

Capacitors

High-value bypass capacitors to be integrated via thin film techniques are a challenge. For frequencies exceeding the 100 MHz range, thick film solutions show an increasing dielectric dispersion, therefore thin film capacitors are superior. Integrated thin film capacitors may exist of a sputtered conductive bottom electrode, an RF, or a reactively sputtered dielectric layer such as AlN, Al_2O_3, Si_3N_4, SiO_2, or Ta_2O_5, and a conductive top electrode. Generally, a great variety of metal/insulator combinations is possible, depending on the technical requirements and the compatibility with the materials below and above the capacitor.

Unified solutions with only one base material are Ta // Ta_2O_5 // Ta or Al // Al_2O_3 // Al, which could theoretically be performed with only one sputter source, using the technique of reactive DC or RF sputtering. More sophisticated solutions have electrode stacks, including adhesion layers as well as barrier layers. Typical electrode materials are either good conductors, such as Al, Au, Cu, Pt, or perform a good adhesion, such as Cr, MnO_2, Nb, Ta, Ti, and TiW. Additional barrier layers to avoid diffusion and migration – once between the surrounding of the capacitor and second between conductor and insulator of the capacitor itself – are materials such as Ni, NiCr, Ta_xN, TiN, TiO_x, ZrO_2, and many more.

Suitable dielectrics for capacitors have a high insulation resistance $> 10^{12}$ Ohm · cm, a high dielectric strength, and a high dielectric constant. Ta_2O_5 has a very high dielectric constant of 25 (at 100 kHz), followed by Al_2O_3 with 9 and Si_3N_4 with 8. With a thickness of only ~ 200 nm, breakdown voltage values of 50 V are reported with Ta_2O_5 and Si_3N_4, achieving a dielectric strength of 3 to 5 MV/cm. The achievable capacitance per square is comparable to thick film capacitors. However, the thin film version appears much more stable and better suited to high-frequency requirements.

Conclusion

When it comes to integrated thin film circuits, state-of-the-art technology is guaranteed with a Unaxis sputter deposition system, whether a load lock batch system such as LLS EVO or a single wafer system such as the CLUSTERLINE®.

All coated substrates distinguish themselves through

- Very low TCR
- Excellent long-term stability
- Low stress
- Extremely tight tolerances
- High uniformity
- Small critical dimensions
- Highly reproducible values from substrate to substrate and from batch to batch

High uniformity, high process flexibility, excellent yield, and easy-to-service equipment with high up-time are the advantages that speak for an economical integrated passive thin film solution.

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