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Future Directions for High Temperature Electronics

7.1 Semiconductor Devices

The preceding chapters in this book have demonstrated the capabilities for designing, manufacturing and testing an application specific semiconductor device based on SOI process technology for application in high temperature aero-engine control. The SOI semiconductor process suitable for high temperature operation is not widely available, with a limited number of foundries worldwide. As demand for niche applications with their low production quantities does not interest mainstream semiconductor companies, this situation is likely to remain in the future, unless even this demand is insufficient, causing existing foundry capabilities to be declared obsolete.

Alternative semiconductor materials and processes are being developed for high temperature applications, such as SiC and GaN, but the process complexity is restricted and further developments will be required to reach the current capability of the high temperature SOI process. As the markets will continue to be niche, low production quantities, the pace of device capability development will be governed by the ability to fund specialist application requirements rather than a widespread demand for the technology.

7.2 Passive Components

In parallel to the development of semiconductors for high temperature applications, advances have been made in extending the capabilities of passive components, such as capacitors, resistors and inductors.

For capacitors, ceramic based high dielectric materials have been developed with operating temperatures of up to $300-400°C$, although derating of capacitors values need to be taken into account and lifetimes at these temperatures under voltage bias need to be established. Silicon capacitors are also attractive for stability at operating temperatures of up to 250−300°C. Overall capacitor values at temperatures of $>$250°C are limited to $<$10 μF and there does not seem to be many prospects for higher value capacitors operating above this temperature.

For resistors, precision thin film resistors are available for operation up to 250°C, with temperature limitations imposed by the materials used in the assembly of the resistors, including resistance shifts of the thin film resistor on ageing and deterioration of the high temperature adhesive used to attach the thin film resistor to a ceramic substrate. For general resistors, thick film resistor materials can be relatively stable up to 400°C. Other passive components, such as inductors, are available from a limited number of suppliers with an upper temperature limit of around 250°C.

7.3 1st and 2nd Level Assembly

For long-life products, such as required in aero-engine controls, the durability of the materials and connections used in the assembly of systems needs to be established, covering 1st and 2nd level processes. Long-term ageing tests have been carried out at 250°C, showing negligible deterioration for ageing periods of up to 1 year, but with predicted lifetimes of 25 years, higher temperature ageing studies to provide accelerated degradation factors are required. Within the demonstration unit, Al-1%Si wires were used to interconnect the ASIC to the metallisations on the package/substrate. Although the wire bonds were stable at 250°C, at temperature exposures of >300°C, the Al based wires would soften and alternative wires such as Au and Pd would need to be examined, along with custom compatible metallisations. For die attach and surface mount passive components, most high temperature adhesives do not provide long term durability at temperatures of 250°C and above. Attach with non-organic materials such as Au-Si eutectic, Ag-glass or possibly sintered Ag is recommended. For the 2nd level assembly processes, high melting point Pb based solders are used, although there is interest in developing Pb free alternatives, but there are few materials available capable of operating above 250°C.

7.4 Custom Metallisations

High temperature devices and components are normally supplied with a standard metallisation, based on the accepted practices of the manufacturer.

These metallisations are not always the most suitable for high temperature application when the interconnect materials are considered. As a rule of thumb, mono-metallic systems connecting the device/component to the package/substrate are desirable, but rarely achievable and a compromise has to be reached. In addition, diffusion from within the metallisation structure must also be taken into account for possible interaction between the connection and the device/component/substrate/package material, which can cause deterioration over time. It is recommended that device/component/substrate/package metallisations and interconnect systems are thoroughly reviewed to ensure compatibility or to conduct tests where there are doubts about long-term durability. It is possible sometimes to request custom metallisations from the device/component/package/substrate supplier, normally with a price penalty and subject to Minimum Order Quantities.

7.5 EMI/Lightning Protection

Alongside the specific devices and components for high temperature aero-engine control systems, protection against transients caused by EMI and lightning strikes must be catered for. At present, there is a dearth of components that can fulfil this function. Specialist devices (normally based on SiC) are in development at the major aero-engine manufacturers, although these devices are not yet proven and qualified. Until devices become available, EMI/Lightning protection will need to be provided away from the hot zone containing the engine control system, with additional costs, weight and losses of cabling.

7.6 Applications

The aero-engine control system developed and demonstrated has several common features that could be applied to other multi-sensing systems in different industry sectors, including down-well exploration and monitoring, gas turbine instrumentation, automotive engine and braking control systems and geothermal extraction. Although the environmental requirements for each application are different in detail, the overall design selection will always be based on integration of off-the-shelf components or custom design on silicon through an ASIC. The building blocks used in this ASIC can be reused in other applications, thus cutting down on design time and making the design process less application specific.

7.7 Commercial/Environmental Factors

7.7.1 Market Size

The market size for high temperature electronics based on aerospace and down-well applications has been growing gradually for many years. Although this growth in applications is positive, it is insufficient to attract significant interest from the major semiconductor foundries and supply of devices will remain in the realm from the niche semiconductor manufacturers at relatively high prices. An increase in demand for high temperature semiconductor devices from the automotive sector will broaden the range of foundry capabilities and reduce prices, but not to the extent of commodity prices seen in consumer electronics.

7.7.2 Custom vs Discrete Solutions

The product development cycle in most electronics applications normally involves breadboarding a particular solution using discrete off-the-shelf devices and components mounted onto a printed circuit board, before progressing towards an ASIC if the production quantities justify the design and manufacturing costs against a lower unit cost. In the field of high temperature electronics, the range of off-the-shelf devices is limited and the combination of discrete devices may not satisfy the application requirement. This situation leads towards adoption of custom electronics through an ASIC design earlier in the product development cycle. Design re-use or common building blocks which can easily incorporated into an ASIC will reduce the design time and costs, but there are no current examples of a high temperature gate array approach, where customisation takes place within the top metal layers during ASIC manufacture. Multi-Project Wafers are also not that common, as new high temperature designs are sporadic and the high value nature of projects in aerospace and down-well applications will normally justify a dedicated engineering wafer run, which, if successful, can also satisfy initial production quantities.

7.7.3 Integration into Systems

The connection of the high temperature electronics control unit into the overall system will normally by achieved through a robust connector (e.g. MIL-DTL-38999), some of which can operate up to 250°C, with the correct selection of materials. If higher temperature connections into the system are required, specialist lead/wire brazing/welding techniques may be required, which would need to be implemented on a case-by-case basis.

7.7.4 Lifetime Support

The lifetime of the product is dependent on the temperature profile experienced by the electronics control unit in service and any other environmental factors (e.g. vibration) that may accelerate deterioration of the unit. The desire is to have electronics that is based on a "fit and forget" principle, but the reality in high temperature electronics is that units may have to be replaced at some stage during the product lifetime. In aerospace, regular checks on the unit performance can be made during scheduled maintenance and replacements are possible. In down-well drilling applications, this can be achieved relatively easily between drilling operations, but for permanent monitoring operations, replacement will be difficult if not impossible.

7.7.5 Economics

The current status of the high temperature electronics market of high value, niche products means that price is not as key as experienced in commodity markets. The limited number of suppliers, low production quantities and specialist materials/processes leads to unit prices significantly higher than other industrial and consumer electronics. In some sectors, uprating of industrial electronics to operate beyond their specified upper temperature limit can satisfy the need for high temperature electronics with short lifetime requirements and provide a more cost effective solution.

In addition to the unit price considerations, the impact of using high temperature electronics can have an overall positive cost benefit for the system. For example, in aerospace, a reduction in weight can lead to fuel savings, and in down-well drilling, increasing the duration of a drilling operation can minimise downtime. Each case needs to be reviewed not just on the unit price, but on the overall system to assess whether there is an economic advantage in investing in a high temperature electronics solution.