Materials Issues of SAW Sensors for High-Temperature Applications
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Abstract—The technology of surface acoustic wave (SAW) devices allows the integration of signal processing and sensor functions within one product. In the past, SAW sensors have been operated at room temperature or 100 °C–200°C at most. Material-related problems become obvious if one attempts to increase this operating temperature to a value as high as 1000 °C. First experimental results will be presented based on a variation of the metallization and the use of diffusion barriers. It is expected that the use of these specially tailored materials with particular functional properties will lead to a considerable improvement of the lifetime and reliability of SAW sensors and the development of devices resistant to high temperatures as well as high pressures and chemically aggressive environments. The high-temperature characteristics of such novel devices are investigated by finite-element simulation and by experimental deformation analysis. It will also be discussed which assembly, interconnection, and packaging techniques are applicable at 1000 °C.

Index Terms—Amorphous materials, amorphous metallic layers, diffusion barriers, electromigration, high-temperature electronics, metallization, surface acoustic waves.

I. INTRODUCTION

SURFACE acoustic wave (SAW) devices are analog RF components operating at frequencies from 30 to about 2500 MHz. Owing to their small size, ruggedness, and good reproducibility under mass fabrication conditions, they have found widespread applications as frequency filters, delay lines, resonators, or correlators, e.g., in TV sets and mobile phones [1]–[4].

Fig. 1 shows a schematic drawing of a simple SAW filter. It consists of interdigital transducers (IDTs) converts an electrical RF voltage applied between the two opposing electrode combs into a SAW (transmitting mode) and vice versa (receiving mode) because of the piezoelectric effect. The IDTs are connected to the package pins by aluminum or gold wire bonds.

Electrical signals passing through an SAW device are modified either by the frequency-selective property of the acoustoelectric conversion process or by propagation effects acting on the SAW. This can also be exploited for sensor rather than signal processing purposes. To this end, one intentionally lets a physical or chemical quantity such as temperature, mechanical stress, or gas concentration influence the acoustic wave [5]–[7].

In the literature, numerous SAW sensors have been described. Most of these laboratory specimens are based on the above-mentioned standard substrate and electrode materials as well as assembly and interconnection technologies. Quite a few applications, however, call for sensors that are able to withstand high temperatures. In the case of industrial process chambers or automobiles, these temperatures may reach values up to 1000 °C.

II. MATERIALS ISSUES

The conventional SAW materials cannot be employed in such environments: the substrate materials undergo phase transitions or dissociate too fast around 500 °C. Aluminum softens, silicone adhesives are not temperature stable, and the dielectric insulation of metal package pins and the metal multilayers in ceramic surface-mount technology (SMT) packages are destroyed by elevated temperatures. In view of the above facts and in order to realize high-temperature SAW sensors, one needs to improve all components of the acoustic microsystem, i.e., the substrate, planar electrodes, and assembly and interconnect technology.
A. High-Temperature SAW Substrates

In a first step, we investigated the temperature range within which the standard SAW substrate materials quartz and LiNbO$_3$ may be employed [8]. Quartz is limited to temperatures below about 500 °C because the material undergoes a phase transition from its $\alpha$- to the $\beta$-modification at 573 °C. Similarly, LiNbO$_3$ test delay lines showed an increasing attenuation starting at about 550 °C, which is attributed to material degradation.

These results underline the fact that a new (piezoelectric) substrate material must be used if an SAW sensor has to perform at temperatures as high as 1000 °C. We have extensively studied langasite, La$_3$Ga$_5$SiO$_{14}$ (gallium lanthanum silicate), in this respect and have obtained intriguing results. For instance, the material itself did not exhibit any changes in the crystal lattice after having been exposed to 800 °C for four weeks continuously.

To study the high-temperature behavior of SAWs on langasite, we used test delay lines with Pt electrodes. To obtain a better (long-term stable) solution, the chips were placed in a commercial SMT package and contacted with Pt wire bonds. Although the package does not withstand temperatures above 600 °C in the long run without being destroyed, this setup could be used to conduct basic experiments (Fig. 2).

The test devices were subjected to temperature cycles between room temperature and more than 1000 °C, and their scattering parameters were recorded by a Hewlett Packard vector network analyzer. As it turns out, the center frequency of an IDT with 50-nm Pt electrodes on langasite depends quadratically on the temperature, the turnover point being located around 250 °C [Fig. 3(a)]. At the same time, the insertion attenuation first decreases somewhat and then starts to rise at 600 °C, but the device works until about 1000 °C [Fig. 3(b)]. The rise in attenuation is attributed to the gradual destruction of the SMT package, which leads to a deposition of metal particles on the SAW chip surface.

The above results clearly demonstrate that SAW devices on langasite have the potential to withstand very high temperatures. As a result of the experiments, it can be stated that, at present, the high-temperature operation is not limited by the substrate, but rather by the packaging problem and by migration defects in the Pt electrodes.

To prove that an actual SAW sensor can be realized with Pt electrodes on langasite, we designed and fabricated a 3-bit ID tag with response peaks at about 3, 5, and 7 $\mu$s. For comparison, the tag was fabricated with both Al and Pt electrodes. The measured device characteristics are ample evidence that sensors
Fig. 4. Impulse response of a 3-bit ID tag on langasite with Al electrodes (dashed line) and with Pt electrodes (solid line).

B. Metallization/Diffusion Barriers

The application of SAWs in high-temperature, high-pressure, or corrosive environments puts high demand not only on the substrate but also on the metallization layer for the electrodes. Disturbing processes related to the atomic transport along grain boundaries and mechanical hysteresis can be avoided by the use of amorphous materials.

In sensor technology, these new materials promise an effective improvement of the long-term stability of the metallization under extreme environmental conditions, e.g., extreme mechanical loads for pressure sensors. With the conventional Al-metallization the long-term lifetime is limited by diffusion processes (electromigration) along internal interfaces or at the surface. Those processes are caused by the mechanical response to surface acoustic waves and high electric current densities with further miniaturization. The migration of material leads to the formation of voids that can cause an interruption of the electrodes and to the formation of hillocks on the surface leading to short circuit. Because the preferential migration paths are located along the grain boundaries, these problems are increased if the width of the electrodes corresponds to the size of the grains in the metallization layer. It is expected that this kind of damage can be considerably reduced by the application of amorphous materials without grain boundaries.

These have to be compatible with established photolithographic techniques.

Often, extreme service conditions prevail such as high temperatures, aggressive surrounding media, and high current densities which require excellent contact resistance on long time scales, good adhesion between the metallic circuits and the substrate, negligible fatigue of materials used for membranes or mechanical switches, and good creep resistance of conducting interconnects and bonding materials.

In order to prevent unwanted reactions between the substrate and the metallization at elevated temperatures, the use of diffusion barriers becomes necessary. Based on the experience from very-large-scale integration (VLSI) technology, but also from the high-temperature applications of wide-bandgap semiconductors, the most stable and longest lasting barriers have an amorphous atomic structure.

In addition, the barrier must also be mechanically compatible with its environment. To avoid cracking and delamination, the barrier should be under low stress and possess good adhesion. The coefficient of thermal expansion should be matched to the surrounding materials as closely as possible.

Considering these circumstances, the most promising diffusion barrier is amorphous Ta–Si–N with a typical thickness of 100 nm containing generally compressive stresses [9]. As metallization, we have chosen Pt due to its better temperature stability in comparison with Al or Au. The thermal expansion coefficient of Ta₃₀Si₁₄N₃₀ is typically 6 ppm/K [10]. The crystallization temperature, i.e., the temperature up to which Ta–Si–N films can be used as diffusion barriers, corresponds to about 950 °C.

C. FEM Simulation

Nonlinear finite-element simulations considering the nonlinear, temperature, and rate-dependent behavior of different materials used (metals, polymeric, and interconnect materials) and experimental investigations have been utilized for deformation and failure analysis under several low- and high-temperature conditions. Considering this, nonlinear finite-element analysis (FEA) gives the basis for the evaluation of strongly localized stress/strain fields in thermally loaded assemblies by several adapted failure models.

In order to make sure that finite-element modeling is adequate to real component conditions comparison of finite-element results with deformation or stress measurements is desirable. Consequently, some results have been compared to strain measurement results obtained by the so-called micro deformation analysis by means of correlation (DAC) measurement method. This method needs nearly no surface preparation and allows deformation measurements under different thermal and mechanical loading situations. In this way, the combination of numerical simulation with experimental investigations helps to better understand manufacturing-induced stresses and failure mechanisms. The first finite-element simulations deal with the stresses and strains in the encapsulated SAW assembly induced by the assembling procedure. Fig. 5 shows the deformation of
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II. EXPERIMENTAL

As a substrate for applications up to 1000 °C, monocristalline langasite (La$_3$Ga$_3$SiO$_{14}$) was used because it does not lose its piezoelectric properties up to this temperature. The metallization layer was made of Pt. Between the metallization layer (electrically conducting) and the substrate a Ta–Si–N alloy was located as a diffusion barrier. This amorphous layer can be manufactured by reactive sputtering. As such, 100-nm-thick Ta$_{44}$Si$_{18}$N$_{38}$ films have been deposited on langasite substrates with an additional Pt thin film (100 nm) on top as metallization. The Ta–Si–N thin films were investigated by depth-sensitive nano-indentation methods, atomic force microscopy, and X-ray diffraction.

IV. RESULTS AND DISCUSSION

The roughness and the hardness play a crucial role for the quality of the interconnections. Fig. 6 shows the surface roughness of the amorphous Ta–Si–N films with Pt deposits. The height variation is 43 nm. The hardness is measured with a depth-sensitive indentation method. The typical indent on the Ta–Si–N film is shown in Fig. 7. The triangular trace on the indent, stemming from a Berkovich tip, is typical for these types of measurements. In Fig. 8, the hardness of the sample is shown as a function of indentation depth.

The room-temperature Cu–K$_{\alpha}$ X-ray grazing incidence diffraction pattern of the sample is illustrated in Fig. 9. The diffraction pattern shows sharp Bragg peaks for the substrate and the Pt film, but no crystalline peaks for the Ta–Si–N layer, indicating that the Ta–Si–N layer is completely amorphous. The thermal stabilities and amorphous structures of the Ta–Si–N thin films strongly depend on the N content in the Ta–Si–N thin films [11]. When the N content is higher than 25 atm%, the nanostructure is maintained after annealing, because N atoms hinder the crystallization of the Ta–Si matrix through the breaking process of Ta-silicide and the binding mechanism of N, Ta, and Si. The Pt-layer is strongly textured in the ⟨111⟩ direction.

Reference [11] has shown that the Ta–Si–N is stable up to 950 °C on Si substrate if the N composition is chosen correctly. Fig. 10 exhibits an X-ray diffraction pattern of Ta–Si–N films with 19 and 40 atm% N content. The 40-atm% N composition has not crystallized at 1100 °C.

It has already been stated that commercially available SMT packages both of the metal and the ceramic type have been found to be unsuitable for high temperatures. This is illustrated by the pictures shown in Fig. 11. Consequently, except for laboratory experiments, one must come up with an assembly and interconnect strategy that avoids commercial packages. We have followed different approaches, none of which can be said to represent the single best solution under all circumstances. One approach is to glue a crystal lid onto the SAW substrate chip with the help of a ceramic adhesive. The substrate and the lid should consist of the same material (e.g., langasite) and the adhesive is...
chosen such that its thermal expansion coefficient matches that of the crystals. Unfortunately, unlike the adhesive, the piezoelectric crystals are anisotropic; hence, a perfect matching of the thermal expansion coefficients can only be achieved in one direction, and the layered system, substrate–adhesive–lid, will necessarily suffer from thermal stresses at high temperatures.

Nevertheless, preliminary tests showed the feasibility of this packaging technique. For this reason, detailed experimental and theoretical (based on FEM calculations) investigations of the layered system at 1000 °C have been performed.

Until now, it is not clear whether langasite can be direct bonded like silicon (a well-known standard process) or LiNbO$_3$ [12]. The method, if successful, would be of great use for high-temperature sensors. This is because no material other than langasite would be involved in the package, so there exists
no problem with the different thermal expansion coefficients of different media.

REFERENCES


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A. Dommann, photograph and biography unavailable at the time of publication.