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Novel Solution for High Temperature Dielectric Application to Encapsulate High Voltage Power Semiconductor Devices

Vivek Chidambaram^{*1}, T. Jing², Yang Ren Bin³, Maziar Shakerzidah⁴, Lim Kuan Hoong²

Abstract—Traditional semiconductor packaging techniques and materials have been working well for conventional Si devices, which usually operates at temperatures up to 175°C. As the operating temperature increases, these techniques exhibit failures such as bulk flows, volume shrinkage, brittleness and subsequent cracking and deterioration of dielectric strength. For the new wide band gap power devices, which work at voltages as high as 1200V and junction temperatures as high as 250°C, there is currently no known dielectric material to encapsulate and protect the active devices. This paper summarizes novel solutions for high-temperature dielectric materials for encapsulating high power semiconductor devices without any dielectric breakdown and also without introducing excessive thermal, electrical and mechanical stresses to the encapsulated devices. Polymer dielectric candidates investigated in this study include cyanate ester based resin and silicone based resin. In addition, conformal coating approaches that include alumina deposited by atomic layer deposition (ALD) technique and tetrahedral amorphous carbon (ta-c) deposited by filtered cathodic vacuum arc (FCVA) technique were evaluated in this work. Dielectric strength performance of the material combinations with respect to temperatures were evaluated.

Among the polymer encapsulants, silicone resin with silica fillers was determined to be the prospective candidate. Breakdown voltage and leakage current of the silicone based encapsulant, with and without the conformal coating was measured by breakdown tests. It was determined that the ta-c conformal coating deteriorates the dielectric performance of the encapsulant, while the alumina thin film deposited by ALD approach reduces the leakage current of the encapsulation material and also increases the breakdown voltage of the silicone encapsulant. Thus, the combination of alumina thin film deposited by ALD approach along with the silicone encapsulant is recommended for this application, involving high temperature and high-voltage.

Index Terms— Encapsulation, dielectric strength, conformal coating, dielectric breakdown, leakage current

I. INTRODUCTION

DIELECTRIC materials are used to encapsulate active devices. There is currently no known dielectric material that can encapsulate and protect the active devices which can work at voltages as high as 1200 V and junction temperatures as high as 250°C. Several encapsulants are claimed to have maximum operating temperatures above 250°C. However, material properties are reported to degrade slowly at such operating conditions.

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Most of the recent developments published are aiming to increase the maximum operating temperature with little focus on dielectric strength improvement. None of the commercially available encapsulants, moulding compound, potting compound and globe-tops possess dielectric strength >10 kV/mm [1-3]. Here, an attempt has been made to achieve a targeted dielectric strength of >20kV/mm at 250°C by combining conformal coating along with polymeric encapsulant. A reliability study is performed in order to ensure that the targeted threshold value is sustained. Two different types of conformal coatings for enhancing the dielectric strength were also evaluated.

Cyanate ester based resin, and the silicone based resin with different filler materials were chosen for evaluation since both are high-temperature resins [4]. Common filler materials studied in this work are silica, alumina and quartz. Conformal coatings such as alumina deposited by atomic layer deposition (ALD) and tetrahedral amorphous carbon (ta-c) deposited by off plane double bend filtered cathodic vacuum arc (FCVA) technique were evaluated in this work. The selection of conformal coating material was based on high dielectric strength. Silicone based resin with silica fillers met the targeted value of 20kV/mm dielectric strength at 250°C.

Breakdown measurement tests confirmed that the combination of alumina thin film deposited by ALD technique along with the silicone resin with silica fillers resulted in better dielectric performance. Devices with alumina conformal coating, used in conjunction with silicone encapsulant showed 70% decrease in leakage current and 5% increase in the breakdown voltage. On the contrary, ta-c conformal coating deteriorated the dielectric performance of the silicone encapsulant. Thus, the combination of alumina conformal coating and the silicone encapsulant is recommended for encapsulating high-power semiconductor devices.

II. MATERIALS AND METHODS

1200V Schottky rectifier diodes with thick Al wire bonding were used for this study. Thick Al wire bonded Schottky rectifier diode attached to the ceramic substrate is illustrated in Fig. 1. Electrodes were designed and fabricated for dielectric strength measurements. The voltage rod electrodes are sphere-ended with 5 mm diameter and made of gold-plated steel. Under the test sample is the ground plane electrode. Tests fixtures were made to place the electrodes in an oven for temperatures up to 250°C. The five rod electrodes are separately connected to instruments outside the oven and a voltage was applied to each electrode, one at a time. High voltage was increased linearly at a rate of 100 V/s until a breakdown occurred, before switching to another electrode to test at another location on the same sample. The dielectric

strength of one location is obtained by dividing the breakdown voltage with the local thickness. Five locations were tested to obtain the average dielectric strength of the dielectric at one temperature. Before changing to another temperature within the oven, the electrodes were moved to virgin locations where there had been no electric stress applied [5]. The dielectric strength measurement set-up is illustrated in Fig. 2.

Fig.1. Schottky rectifier diode with thick Al wire bonding (a) front side (b) back side.

Fig. 2. High-temperature dielectric strength measurement set-up.

FCVA is a physical vapor deposition technique, which uses arc to generate the plasma. A pure graphite cylinder is used as the cathode and anode by a graphitic striker. As a result of the high energy arc, highly ionized carbon plasma is formed. The plasma is guided to the substrate using the electromagnetic filter applied to be double bend filter while the micro droplets formed as a result of arc are filtered using the filter walls. The achieved thickness of the ta-c conformal coating is 80 nm. More detailed information about FCVA can be found elsewhere [6-11]. Dielectric strength of the carbon films was measured by ellipsometry.

ALD is a vapor phase technique where two or more chemical precursors are introduced into a chamber in a sequential and cyclic manner in order to react in a self-limiting way on the surface of a substrate to obtain a desired type of film. The flex ALD system from Azimuth Technologies Pte. Ltd is used for

this work. This is a thermal only ALD system with 5 precursor delivery lines. The chamber temperature was kept at 170°C for all experiments. During the optimization process, alumina films were deposited onto the silicon wafers and their corresponding thicknesses were measured using ellipsometry. The growth rate achieved in this study is about 0.10-0.13 nm per cycle.

Reliability evaluation includes high-temperature thermal aging and high-temperature thermal cycling. Thermal aging was carried out at 250°C for 100h. Thermal cycling was performed between -65°C to 250°C for 500 cycles.

III. POLYMERIC ENCAPSULANT SYNTHESIS

Cyanate ester resin and silicone resins were evaluated in this work, since these are proven resins for high-temperature application. Alumina, silica and quartz are the three different filler materials used in this work. Shape of the quartz filler used in this evaluation is angular. Size of the quartz filler used is < 10 μm . Shape of the silica and alumina fillers used in this evaluation is spherical. The average size of the spherical filler used is 20 μm . Two types of adhesion promoters were used. Similar adhesion promoter was used for quartz and silica fillers while different adhesion promoter was chosen for alumina fillers. Delamination of alumina fillers was observed during thermal aging and thermal cycling. Primary root cause is associated with the incorrect selection of appropriate adhesion promoter.

Higher shear strength was observed for resin with quartz fillers. Primary reason for this effect could be attributed to the size of the fillers. Quartz fillers are much smaller than alumina and silica fillers. Smaller fillers possess larger contact surface area. This could be the reason for higher shear strength involving quartz fillers. Moreover, the density of quartz fillers is also relatively lower than the alumina and the silica fillers. Higher density of the fillers is not recommended, in order to mitigate the settling down behavior of the fillers. Despite all these advantages, major drawback of the quartz fillers is the angular shape, where the sharp corners act as stress concentration points resulting in the failure of the resin. Thus, quartz fillers is not recommended for such application. Alumina or silica fillers are preferred. The two modes of failures commonly encountered are bulk resin failure and filler delamination, illustrated in Fig. 3. Bulk resin failure is usually encountered during thermal cycling as a result of the presence of stress concentration points. Angular shape filler is the primary contributor of stress concentration points (Fig. 3a). Filler shape is critical for thermal cycling environment. Selection of spherical fillers will help to resolve bulk failure during thermal cycling. Delamination of fillers from the resin could be resolved by the selection of appropriate adhesion promoter (Fig. 3b). Adequate adhesion promoter is required to be added in the composition.

In addition to selection of the appropriate resin, filler and adhesion promoter, the other key additive is curing promoter or hardener. This additive plays a decisive role for high-temperature thermal stability. Curing process is optimized with the objective of outgassing all the solvents, else it will be

trapped as voids. Generally, the usage of solvents is much lower for cyanate ester and silicone resin when compared to conventional epoxy resin. It is the key reason for them to qualify for high-temperature applications.

Fig. 3 Common modes of failure (a) Bulk resin failure (b) filler delamination from resin

IV. CONFORMAL COATINGS

The mechanical, electrical and optical properties of carbon films depend on the bonding structure of the film [8-10]. It is proven that higher sp^3 content in the microstructure of the film leads to superior mechanical properties (such as hardness and scratch resistance) as well as wider electrical and optical bandgap and lower conductivity. Carbon films were deposited at different substrate biases with the objective of achieving highest sp^3 hybridization. The carbon film deposited at 100V bias showed the highest G peak position in Raman spectra taken by at 514 nm, which can be correlated to the highest sp^3 content [11]. The dielectric constant varies between 6.1 and 6.5 depending on the bonding structure.

Fig. 4. (a) Raman spectra of the as deposited and annealed films (b) Fitted G band center.

As the targeted application involves high-temperature, it is critical to study the thermal stability of the films. As such the thermal stability of FCVA grown carbon films deposited at 100V bias was studied using visible Raman spectroscopy. The deposited films were annealed at different temperatures under air atmosphere for 10 hours. The Raman spectra of the films were acquired before and after thermal annealing. The Raman spectra of the as deposited and annealed films are shown in Fig. 4a. The change in the intensity can be attributed to the small changes in the optical properties or density of the films. The intensity of the film has increased by annealing. As the G peak position remains unchanged, the structure of the film has not changed significantly but variation in the peak intensity is

possibly due to the slight decrease in density or changes in optical properties of the films.

The Raman spectra were fitted by a BWF and Lorentzian curves as G and D bands respectively. The fitted G band center is shown Fig. 4b. As it can be observed, annealing of the films up to 400°C does not have a significant effect on the Raman spectra and the G band position varies negligibly in the range of 1568-1572 cm^{-1} . Annealing of the film at 450°C on the other hand results in total oxidation of the film and no Raman spectra could be acquired. This in turn shows that the carbon film can be safely used at temperatures as high as 400°C.

Fig. 5. Dielectric strength of amorphous carbon versus temperature.

Dielectric strength of the ta-C films deposited under optimum conditions by FCVA technique was determined to be 120 kV/mm, which is much higher than the targeted dielectric strength of 20kV/mm. However, significant degradation was observed, when subjected to thermal aging at 250°C (Fig. 5).

Alumina conformal coating by atomic layer deposition was chosen for evaluation due to high dielectric strength, high temperature stability ($>2000^{\circ}C$), excellent moisture barrier, and good adhesion to semiconductor and metal. Different sets of parameters were evaluated with the objective of being conformal, self-limiting and uniform. Electrical breakdown performance for each of these films was measured. Selection of appropriate process was based on the highest dielectric strength.

Among the two evaluated processes, the first process uses about 97% Trimethylaluminum (TMA) and H_2O as the precursors. The second process uses the same TMA precursor with ozone (O_3) instead. Both processes resulted in dielectric strength much higher than 20kV/mm (Fig 6).

Alumina film deposited using ozone precursor resulted in higher dielectric strength. Irrespective of the deposition processes, significant reduction in dielectric strength was observed with increasing temperature. However, the reduction in dielectric strength with respect to temperature was linear. Despite the linear reduction, while using O_3 as the second precursor, average dielectric strength is higher than using the conventional H_2O as the second precursor. The improved dielectric strength achieved for the Al_2O_3 film deposited using

the TMA+ O₃ precursor, when compared to the TMA+H₂O film could be attributed to the larger number of defects in the latter. Al₂O₃ by TMA + H₂O has been shown to contain significant amounts of hydrogen, particularly at lower temperatures [12]. These hydrogen impurities (~5 atomic % at 200C) [12] in the form of hydroxyl groups might undergo disassociation, under thermal and electrical stresses [13]. Together with a higher concentration of Al-Al defect sites [14], leakage currents in TMA+H₂O films have been shown to be larger, when compared to the film deposited by TMA+O₃ [15]. Thus, the process with the TMA and ozone were selected for the alumina conformal coating deposition. Relative dielectric strength of the deposited film is **measured or calculated?** as 7.2.

Fig. 6. Dielectric strength of alumina films using different precursor combinations vs temperature.

V. THERMAL AGING/ CYCLING OF POLYMERIC ENCAPSULANTS

Cyanate ester resin with quartz and alumina fillers and silicone resin with silica fillers were subjected to thermal aging at 250°C for up to 100 h. Severe degradation was observed for cyanate ester resin with alumina fillers, when subjected to thermal aging at 250°C for 50 h. Hence, it was not subjected to aging until 100h. Thermal stability and the corresponding dielectric strength with respect to thermal aging duration at 250°C is evaluated. Change in color during thermal aging indicates the onset of thermal degradation.

Gradual change in color was observed for cyanate ester resin with quartz fillers as illustrated in Fig 7. Drastic change in color was observed for the cyanate resin with alumina fillers, when subjected to thermal aging at 250°C (Fig. 8). No change in color was observed between the samples which were subjected to thermal aging at 250°C and without thermal aging for silicone resin with silica fillers (Fig. 9). This clearly indicates the thermal stability of the silicone resin with silica fillers. Poor performance of the cyanate ester resin with the alumina fillers, when compared to the alumina fillers could be attributed to the selection of appropriate additives in particular adhesion promoter and curing promoter.

Fig. 7. Cyanate ester resin with quartz filler with and without thermal aging (a) without thermal aging (b) 250° for 50 h

Fig. 8. Cyanate ester resin with alumina filler with and without thermal aging (a) without thermal aging (b) 250°C for 50 h.

Fig. 9. Silicone resin with silica fillers with and without thermal aging (a) without thermal aging (b) 250°C for 100 h.

Dielectric strength performance of prospective candidates versus different thermal aging conditions are illustrated in Fig. 10. The degradation of cyanate ester resin irrespective of the filler material is confirmed by the dielectric strength measurement results as well. However, the magnitude of degradation varied. Degradation was pronounced for cyanate ester resin with alumina fillers. No degradation was observed for silicone resin with silica fillers. Poor performance of the cyanate ester resin with silica fillers, when compared to quartz fillers could be attributed to the inappropriate selection of additives and their respective composition. No degradation in the dielectric strength was observed for the silicone encapsulant with silica fillers during thermal aging. Thus, the targeted dielectric strength of > 20kV/mm could be achieved by both cyanate ester resin with quartz fillers as well as silicone resin with silica fillers for the temperature regime **of upto** 200°C. However, at 250°C, only silicone resin with silica fillers could meet the requirement.

Unlike the thermal aging at 250°C for 100h, thermal cycling between -65°C to 250°C for 500 cycles was less stressful. Both silicone resin with silica fillers and cyanate ester with quartz fillers could comply with the targeted dielectric strength of > 20kV/mm. However, cyanate ester resin with alumina fillers could not meet the targeted dielectric strength for thermal cycling as well. This could primarily be attributed to the incorrect selection of additive promoters. No deterioration in the dielectric strength was observed for the silicone resin with silica fillers, while minor deterioration in the dielectric strength

was observed for the cyanate ester resin with quartz fillers. This could be attributed to the angular fillers acting as crack propagation sites in the latter during thermal cycling.

Fig. 10. Dielectric strength measurements vs thermal aging conditions for prospective candidates (a) cyanate ester resin with quartz fillers (b) cyanate ester resin with alumina fillers (c) silicone resin with silica fillers.

VI. MATERIAL PERFORMANCE EVALUATION

Breakdown voltage and leakage current were measured with and without the conformal coating on the silicone encapsulant by destructive testing. For destructive testing, the devices were submerged in insulating oil. Applied voltages were increased in steps of 100V at the rate of 50V/s. Dwelling time was 2 min and it was maintained until breakdown. Fig. 11 and Fig. 12 gives the **breakdown** voltage and the average leakage current of encapsulants with and without the conformal coating. It is estimated that the breakdowns occurred in encapsulations rather than the rectifiers due to the difference in leakages and breakdown voltages. Although, the specified reverse voltage of

the rectifier is 1.2 kV, the latter could withstand reverse voltages more than 2.9 kV.

It was determined that the breakdown voltage of the silicone encapsulant was 2933V. ALD deposited alumina was concluded to be an effective conformal coating. It is effective in suppressing the breakdown inception and thereby, reduces the stresses on the silicone encapsulation material. It reduces leakage in the encapsulation material by 70%. Moreover, it also increases the breakdown voltage of the silicone encapsulant by 5%. On the contrary, ta-c conformal coating slightly reduces the **breakdown** voltage of the silicone encapsulation material and also increases the leakage current. Thus, ta-c conformal coating was found to deteriorate the dielectric performance of the encapsulation material. This performance deterioration could be attributed to the re-bonding of C with the device material during coating. Thus, a combination of ALD alumina film deposited in TMA+O₃ environment with the silicone encapsulation material is best suited for this application

Fig. 11. Average breakdown voltage of different encapsulation approaches measured by breakdown tests.

Fig. 12. Average leakage current of different encapsulation approaches measured by breakdown tests.

VII. RELIABILITY STUDY

Stability of the adhesion of the silicone encapsulant with the conformal coatings were evaluated by subjecting the package to thermal cycling between -65°C to 250°C for 100 cycles. Two different package types were evaluated. First type includes the diode with alumina conformal coating deposited by ALD using TMA and ozone as precursors followed by silicone resin with silica fillers as polymeric dielectric. The same polymeric dielectric was also used for encapsulating the rectifier diode

devices. The second package type was similar, with the only difference that the alumina was replaced by ta-c. 5 samples of each type were evaluated. The final assembled package for reliability testing is illustrated in Fig. 13.

Fig. 13. Encapsulated packages for thermal cycling evaluation.

Minor onset of delamination was observed for alumina conformal coating from the silicone resin with the silica fillers (Fig. 14). The adhesion of amorphous carbon to silicone resin remained intact. No change in the interface was observed in the samples subjected to thermal cycling. Although, alumina possessed higher dielectric strength than amorphous carbon, the difference in the coefficient of thermal expansion (CTE) between the alumina and the silicone resin might have resulted in the minor delamination at the interface during thermal cycling. Compatibility of amorphous carbon with the silicone resin with silica fillers is slightly better in terms of adhesion. As the thickness of the alumina coating might have also played a role, further optimization on the thickness is needed in order to avert the delamination at the interface. As the delamination was observed only in few specific locations and no any performance degradation was observed, this issue could be overcome by fine-tuning, the ALD deposition process parameters.

Fig. 14. Adhesion of the conformal coatings with the silicone resin with silica fillers (a) alumina thin film (b) ta-c.

VIII. CONCLUSION

Synthesized silicone resin with silica fillers is rated for high-temperature application. Among the two conformal coatings evaluated in this work, both alumina deposited by ALD technique using TMA and ozone as precursors and amorphous carbon deposited by FCVA technique possessed dielectric strength, several order of magnitudes higher than the targeted dielectric strength of 20kV/mm even at 250°C. Reliability evaluation confirmed that the amorphous carbon is slightly better compatible with the silicone resin with silica fillers in terms of adhesion. However, adhesion of the alumina film with

the silicone encapsulant could be further improved by optimizing the deposition process parameters and corresponding alumina film thicknesses. It was determined that the ta-c conformal coating deteriorated the dielectric performance of the silicone encapsulation, while alumina film reduces the leakage current and increases the breakdown voltage of the encapsulation material. Thus, the alumina conformal coating alone could fulfil both these two requirements and hence, it is recommended for this application. All the above results are verified using the 1200V Schottky rectifier diode.

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