Self-packaged Boron Nitride Capacitor for High Temperature Applications

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Abstract

In this work, we investigated applicability of boron nitride (BN) and boron oxynitride (BNO) thin films to fabricate multilayer ceramic capacitors (MLCCs) for high temperature and high frequency applications. Advantages of BN include high temperature and chemical resistance, which should result in more compact and reliable devices. Deposited BN layers by a filamentless ion source assisted physical vapor deposition technique show a high thermal stability up to 1000 ^{o}C and a very high breakdown voltage of about 600 V/µm. A 15 mm x 15 mm capacitor geometry was picked to create a simpler packaging scheme. Rectangular electrodes are offset and layered to build up the capacitor and a metallization technique is used to produce high temperature oxidation resistant Au/Ti tab electrodes. We have seen consistent results in terms of: stable capacitance values versus frequency from 10 kHz to 2 MHz; near ideal phase angle (low parasitic inductance); and high quality factors values. Laboratory prototype capacitors with operating temperatures (350 ^{o}C - 700 ^{o}C) far superior to the leading sintering technologies (< 200 ^{o}C) were demonstrated. The dissipation factor and the capacitance change within a temperature range of 700 ^{o}C are ~ 2% total and ~10 ppm/ ^{o}C, respectively. Results on thermal and frequency behavior of single and multilayers self-packaged BN capacitors are presented. We have begun testing the capacitor's performance under actual operating conditions, together with other (R and L) components in a working RLC circuit at elevated temperature, and our preliminary results are reported.

Key words

Nitrides, ceramic capacitors, high temperature, energy storage, physical vapor deposition.

1. INTRODUCTION

Electronics operating at temperatures above 200 ^{o}C are identified as critical technology for the 21st century. Silicon carbide and gallium nitride are breaking barriers insofar design and fabrication of high-temperature, high-power transistors but capacitors remain the weak link in achieving higher temperature electronics. Ceramic capacitors are used in high-energy density storage and high frequency power switching device applications [1-3]. High-energy density capacitors operating at excessive temperatures are needed in several critical military applications, such as propulsion and guidance pulse power systems. The need for compact and lightweight pulsed power capacitor devices is a necessity for airborne applications and particularly crucial for space borne.

For high average power applications, capacitor failure is mainly due to thermal "runaway" resulting from internal friction and heat generated as a result of the polarization cycle as the capacitor is charged and discharged under excessive pulse shots. Under these conditions, the temperature of the dielectric rises rapidly and produces localized heating, which reduces the dielectric strength.

Existing MLCCs based on sintering are temperature limited and use expensive precious metals (palladium alloyed with silver) to avoid oxidation of the electrodes since the capacitor has to be fired in air or under reducing atmosphere [4]. Other limiting factor for MLCCs development is that of thickness control and integrity of the dielectric layers as well as effective electrodes; the value of the dielectric being a somewhat secondary consideration. It is thus a requisite to fabricate these capacitor devices out of materials, which exhibit high thermal stability and high thermal conductivity. BN is a material that perfectly meets these requirements [5-8]. BN with excellent mechanical properties and oxidation immunity at elevated temperatures is well suited for applications in harsh environments. The very thin, ultra-high purity dielectric is intrinsically free of defects and has a higher breakdown voltage and lower failure rate than ordinary thick dielectrics. Furthermore, the dielectric can actually be composed of several layers to support fabrication of even higher energy density capacitors.

2. EXPERIMENTS

Capacitors (15mm x 15 mm) based on insulating BN thin layers and conductive aluminum (Al) and tantalum nitride (TaN) internal electrodes were fabricated. The fabrication technique is ion assisted physical vapor deposition (PVD). Beside the BN dielectric layer and metal electrodes, the current process flow requires also fabrication of diffusion barriers made of 0.5µm thick silicon oxide layers deposited by plasma enhanced chemical vapor (PECVD) technique. These intermediate layers will prevent diffusion from the metal electrode through the BN active dielectric layer during either high temperature growth or post growth annealing. Capacitors are deposited on 3-inch silicon and aluminum nitride (AlN) substrates purchased from Accumet Materials Inc. The benefits of the thermal and mechanical capabilities of AlN material make it very suitable for the high-temperature capacitor packaging.

The process flow of making capacitors based on insulating BN thin layers and conductive aluminum electrodes uses a 500 Å thick aluminum layer deposited on a bare silicon substrate through a molybdenum stencil mask with 15mm x 15 mm, openings which correspond to the actual size of the capacitor. In the case of an AlN wafer, two microns thick silicon oxide layer was pre-deposited to smoothen the 1 to 2 µm per inch roughness of as received polished AlN wafer. A diffusion barrier made of 0.5 µm thick silicon oxide layers were deposited on top of the first aluminum electrode by plasma enhanced chemical vapor deposition (PECVD). This is more than twice thicker than the previously 0.2 µm thick layer used for the fabrication of the 3mm x 4mm capacitors [9]. Such change was made in order to account for the increase of the lateral leakage current at a given voltage, which is a function of the electrode size. This oxide layer serves as an intermediate layer to prevent diffusion of the metal electrode through the BN active dielectric layer during either high temperature growth or post growth annealing. Thin dielectric BN films (700 Å) were deposited between the two silicon oxide protective layers using an End Hall ion source (< 100 eV N_2 ions) at a substrate temperature of 350 ^oC and pure evaporated boron (B) material at a rate of 0.5 Å/s. Finally, a second electrode made from Al was deposited similarly to the first electrode. The above procedure can be repeated many times in order to achieve the desired capacitance values for a particular application. The stacked configuration increases the energy density, capacitance, and total energy stored in the capacitor. Similar capacitors using TaN electrodes instead of Al were also fabricated. This is part of our projected plan to make two types of capacitor devices operating at high temperatures. The Al-based capacitors can be safely operated at a temperature up to 400 ^0C, whereas the TaN - based ones will withstand up to 800 ^0C.

Rectangular electrodes are offset and layered to build up the capacitor. A metallization technique is used to produce leads to the electrodes. This capacitor geometry allows for easy alignment, simpler dicing, and can be easily scaled up for larger wafer sizes. We simulated deposition of a conductive layer over the electrodes using indium paste. We believe that deposition of a conductive layer covering the capacitor electrodes along its edge is the most effective way of producing a stand-alone chip. We have begun experiments on deposition of a titanium-gold (Ti/Au) bilayer along the edges and electrodes for this purpose. Elaborated capacitors were electrically and thermally characterized using an HP 4275 A multimeter-frequency LCR meter controlled by a Labview-based program.

We also tested the capacitor's performance in an actual LRC circuit. The unavailability of standard high temperature inductors made it impossible to test the capacitor together with other (R and L) components in a working circuit at elevated temperatures. To counter this problem a circuit was built where the R and L were connected to the capacitor through the electrical feedthroughs available on the thermal test chamber. The circuit consisted of a single resistor (15 Ω ± 0.1%), an inductor (1 mH ± 20%) and the capacitor all connected in series to an external power supply.

3. RESULTS

We have demonstrated multilayer ceramic capacitor structures by making and testing a stack of 5 layer capacitors on silicon using both Al and TaN inner electrodes. The capacitors stack with aluminum electrodes was also subjected to thermal cycling stress to monitor the temporal change in the capacitance. The samples were thermally cycled back and forth from room temperature to 450 ^oC. The change in the capacitance was reversible and no misbehavior due to thermal damage was noticed even under abrupt temperature changes. The capacitance values measured at 10 KHz for 1-layer and 5-layer structures were

1.1 nF and 5.15 nF, respectively. The breakdown voltage (BDV) of the BN -based capacitor reached 600 V/µm. The dissipation factor and the capacitance change within a temperature range of 450 °C are ~ 1% total and ~5 ppm/ °C, respectively. The 5 –layer stack capacitors with TaN electrodes were tested at temperatures up to 750 °C. The capacitance change with temperature was about 10 ppm/ °C within the same range of test temperature. The dissipation factor was about 2 % over the same temperature range. Fig.1 shows the thermal behavior of such capacitor compared to a similar capacitor with aluminum electrodes.

In order to determine the long-term behavior of the capacitor, a typical sample (MLCC#4) was heated to 300 ºC and held at this temperature for a total of 30 hours. At various times during the study, the sample was cooled to room temperature and the equivalent circuit values were measured. Fig.2a summarizes the change in capacitance as a function of annealing time at different frequencies. Fig.2b is the same data emphasizing the change of the capacitance with the measurement frequency at different annealing times.

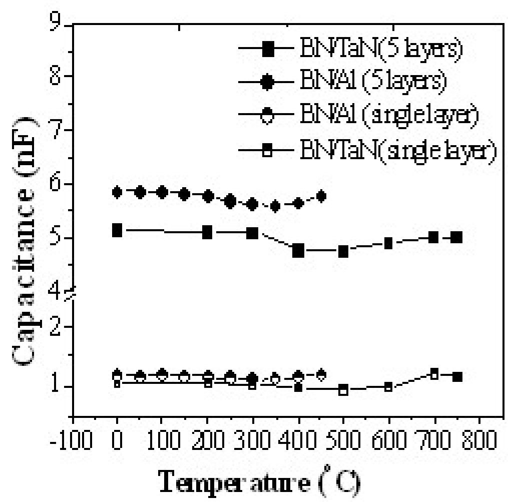

Figure 1. Thermal behavior of single and multilayer capacitors having Al and TaN electrodes

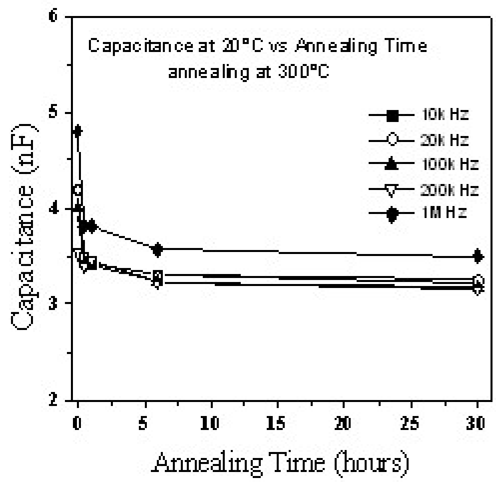

Figure 2A. Capacitance versus annealing time for each of 5 frequencies from 10 KHz to 1 MHz

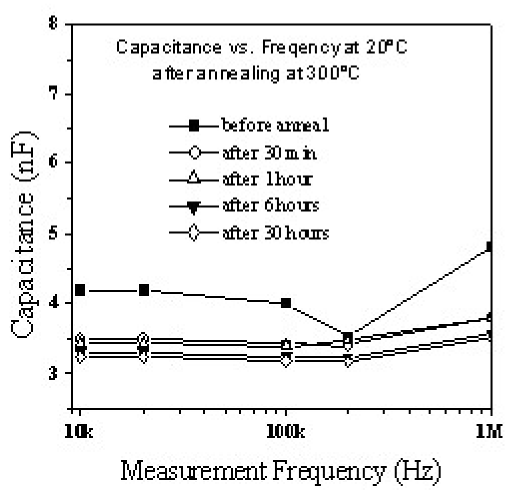

Figure 2B. Capacitance versus frequency for annealing times from 0 to 30 hours

Figure 2. Annealing behavior of capacitance values for MLCC#4

The high-temperature measurements of MLCC#4 were analyzed in order to extract out the time-dependent behavior of the capacitance. All of the capacitance data collected from this sample indicated a two-step behavior in regards to the change in capacitance with the annealing time. This takes the form of an initial rapid change in capacitance in the first 1 to 2 hours followed by a much slower change over the 28 remaining hours. This data has been fitted to a double exponential decay function with two time constants, τ_1 and τ_2. The values for these time constants range from approximately 0.18 to 0.01 hours for the initial decay and from approximately 3.5 to 4.7 hours for the second decay. In summary, the capacitance values for MLCC#4 showed a sharp reduction in values after short annealing times at 300 ºC and slower, smaller reductions upon a longer annealing period.

Measurements on MLCC#5 on an AlN substrate were performed in open air, vacuum, and after annealing at 300ºC for 18 hours. There was a 22% decrease in C at 10kHz after annealing for 18 hours compared to the initial value measured in air, and a 17% decrease in C compared to the initial value measured in vacuum. Capacitance versus frequency measurements are given in Fig.3.

Another capacitor (MLCC#28) with relatively thicker BN layers of 0.1 μm was fabricated on an AlN substrate, coated with 4.5 μm thick silicon oxide layer, diced, and processed using the side edge contact scheme. A 0.25μm thick bilayer of Ti/Au was used as the contact on each side. A very thin layer of Ti is used for enhanced gold adhesion. For this capacitor we performed capacitance versus frequency measurements and compared the results to those from a sample where indium was used as the contact metal (Fig.4).

For the development of a totally in-situ deposition process, we also started investigating the applicability of BNO diffusion barrier layers by using N_2O gas instead of N_2 during B evaporation. This approach simplifies the fabrication process flow by eliminating the need for ex-situ PECVD silicon oxide diffusion barriers. We succeeded in making capacitor structures where the silicon oxide layers were replaced by in-situ BNO. The frequency and thermal dependencies of the first Al/BNO/Al capacitor structure deposited on a silicon wafer is shown in Fig.5. The capacitance is practically constant in a temperature range from room temperature to 450 ^{o}C.

By using higher melting point material for the electrode we should be able to extend the temperature limit beyond that range. The capacitance exhibited also a very small shift in its value as the frequency increased. However, the breakdown voltage is still relatively low to demonstrate higher capacitor performance. From the few samples made so far, it seems that about 25% of oxygen-balanced nitrogen is the limit to achieving a higher breakdown voltage of 550 V/μm but at the expense of good stability and crystalline quality of the BNO layer. We are still optimizing the recipes so that we can make structurally stable capacitor with an acceptable breakdown voltage.

Fig.6 shows the electrical diagram of the RLC circuit used to test the performance of the self-packaged capacitor under actual operating conditions. The capacitor element with a capacitance value of 3.0 nF, was kept inside a thermal chamber at a temperature of ~ 400 ^{o}C. A typical input voltage level from the source generator is about 18 Volts while the signal frequency changed between 1 kHz and 1 MHz. We report in Fig.7 the impedance change plots of the circuit at both room temperature and an actual operating temperature of 400 ^{o}C. Practically no change is seen. The resonance frequency of the RLC circuit is close to 93 kHz, which is quite close to the theoretical value of 92 kHz.

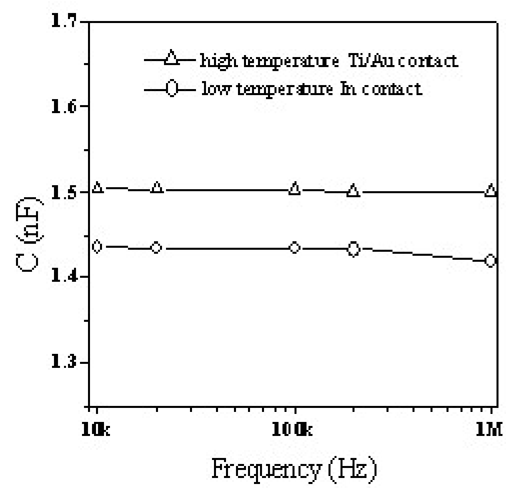

Figure 3. Capacitance versus frequency for MLCC#5 on AlN

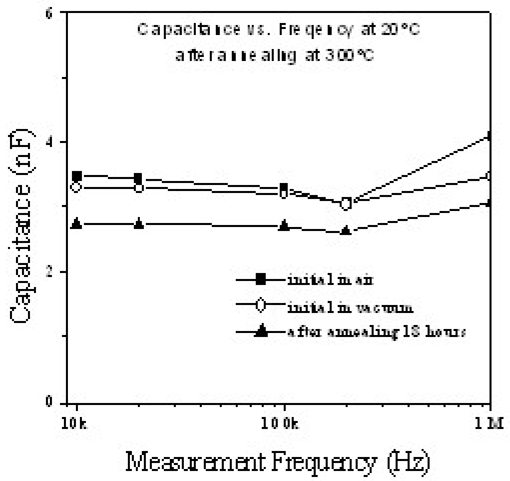

Figure 4. Capacitance versus frequency of packaged capacitors with both In and Ti/Au electrodes

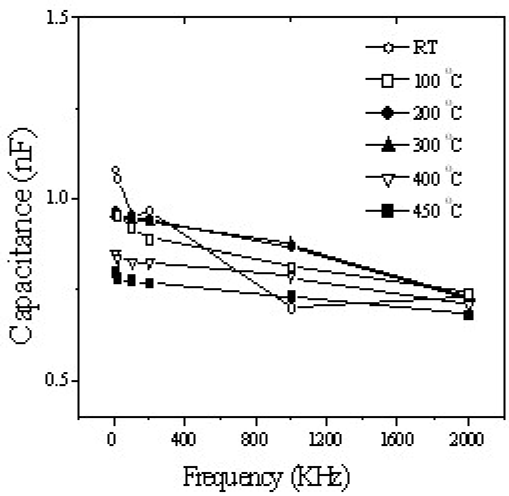

Figure 5. Thermal/frequency response of the Al/BNO/Al capacitor structure deposited on a silicon wafer

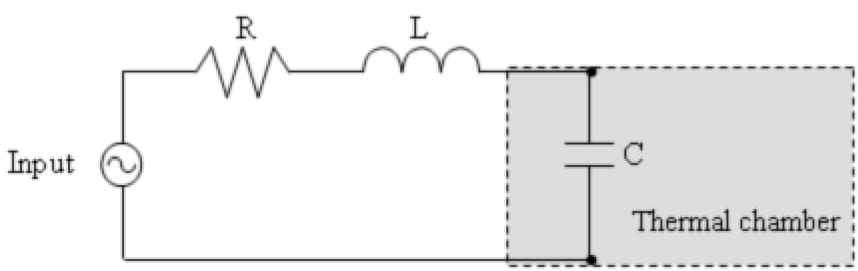

Figure 6. Electrical diagram of typical RLC circuit for capacitor testing

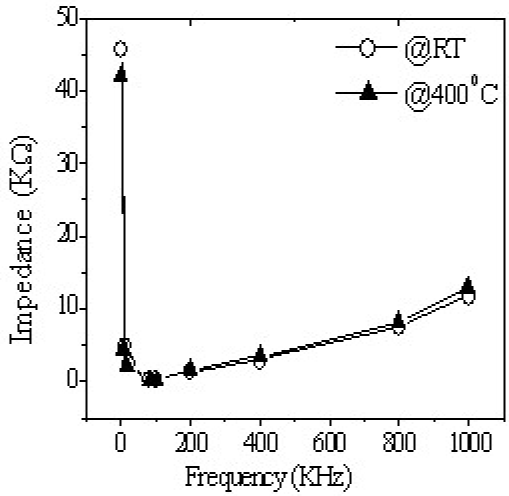

Figure 7. Impedance change versus frequency at RT and 400°C

4. CONCLUSION

High temperature single and multilayer capacitors based on insulating BN thin layers and conductive aluminum and tantalum nitride layers electrodes were fabricated on both silicon and AlN substrates. Electrical characterizations show reproducible and thermally stable capacitor over frequencies up to 1 MHz. The dissipation factor and the capacitance change within a temperature range of 700 °C are ~ 2% total and ~10 ppm/ °C, respectively. BNO-based capacitors were also deposited successfully on silicon substrates. The recipe for making structurally stable BNO capacitors with an acceptable breakdown voltage needs to be optimized. Self-packaged BN –based capacitors have been implemented within an RLC circuit and tested at high temperature. Results so far point to the need for further optimization of the fabrication process to allow much higher performance devices and to develop a strategy to simplify the process flow for large-scale production.

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BIOGRAPHIES

Dr. Nacer Badi has expertise in growing hard coatings and microstructures for high-temperature hybrid microelectronics devices and packaging. Dr. Badi also has an extensive background in computer modeling and simulation. He obtained his Bachelors degree in electronics from the University of Science and Technology of Oran, Algeria in 1989 and his Master's degree in microelectronics from the University of Sidi Bel-Abbes, Algeria in 1992. He started his doctorate program in Materials Science and Engineering and he joined the Space Vacuum Epitaxy Center, at the University of Houston, where he obtained his Ph.D. in Solid State Physics in 1996. Dr. Badi is currently a Senior Research Scientist at Integrated Micro Sensors, Inc., where he is developing advanced ceramic capacitor technology for both high temperature and cryogenic applications. As a Research Assistant Professor with the Texas Center for Superconductivity and Advanced Materials at the University of Houston he develops nitride thin films for tribological and field emission devices applications. Dr. Badi holds 2 patents in the area and has published over 60 peer-reviewed papers.