Development and Characterization of Photodefinable Polybenzoxazole Buffer Layer for InGaP/GaAs HBT Applications

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Abstract

Mechanical damage to the final passivation layer and underlying devices and interconnections is occasionally observed during semiconductor fabrication. This damage can occur during handling, wafer backside processing, and during assembly. Damage can be in the form of scratches, embedded defects, cracks, chip-outs, delamination, which can affect the circuit performance and can lead to lower yield, poor quality and reliability, and higher customer return. We have developed a process for InGaP/GaAs HBT technology using a photodefinable polybenzoxazole (PBO) as buffer layer that is coated on top of the final passivation layer, for effective protection against mechanical damage. The PBO process is manufacturable, is compatible with existing process and tool sets, with minimal additional steps, and uses no additional mask layer. Furthermore, the material has excellent material characteristics and also functions as resist and hardmask during street and bondpad opening etch. Additionally, InGaP/GaAs HBT wafers with MIM capacitors, and with PBO as buffer layer that have been intentionally damaged, have been shown to have minimal capacitor failures even after wafer exposure to high temperature, high pressure, and high humidity autoclave test conditions, compared to the many failures observed on wafers with no PBO buffer layer.

INTRODUCTION

In semiconductor fabrication, polymers are commonly used as dielectric material. These polymers include polyimides and polybenzoxazoles (PBO), which are high performance dielectrics with excellent dielectric, electrical and thermo-mechanical properties, such as low dielectric constant, low stress, high modulus, robust plasma etch resistance, chemical resistance, high electrical resistivity, thermal stability (>500º), high degree of ductility, and inherently low coefficient of thermal expansion [1]-[5]. Due to those characteristics, they have a wide range of applications, including as passivation layer, inter-level dielectric, protective layer, redistribution layer, die attach adhesive, and as flip chip bonding material [1],[3]-[5].

In many cases, polybenzoxazole is preferred over polyimide, as it absorbs less water, and can be cured at lower temperature ($\geq 250^oC$) and still retains its excellent mechanical characteristics [2]. Additionally, PBO has been shown to be a better gapfill and has more planarizing characteristics, compared to most polyimides [2]. This PBO can be made photodefinable with a photosensitizer, which eliminates the need for photoresist and which can be used as hardmask during etching [2]. All the above characteristics makes this material to be suitable for most GaAs technologies.

Typically, in semiconductor fabrication, the top layer or final passivation layer for frontside wafer processing is a thick PECVD silicon nitride (Si_3N_4). This PECVD Si_3N_4 is hard, conformal, and is excellent for protection against moisture absorption [7]-[10]. However, it easily cracks, does not planarize the underlying structures and topography, and can easily be damaged during subsequent processing. Moisture can then penetrate through the damaged area into the underlying devices. The damage can occur during wafer backside processing, such as wafer bonding and debonding, wafer thinning, scribe and break, testing, and during assembly processes, such as during die pick and attach, wirebonding, and mold application. It can be in the form of scratches, embedded defects, cracks, chip-outs, and delamination, all of which can lead to lower yield, poor quality and reliability, and higher customer return.

In this study, we have investigated the use of PBO to mechanically protect the underlying devices and interconnections and to serve as a buffer layer for InGaP/GaAs heterojunction bipolar transistor (HBT) technology. The goal of this study was to improve the integrity of the HBT wafer/die against mechanical damage. The criteria was to have a process that is manufacturable, compatible to existing HBT flow, does not add additional mask layers, has no or minimal additional steps or stages, and has minimal effects on tool set requirements. Furthermore, the reliability of the HBT device wafers with metal-insulator-metal (MIM) capacitors was studied, by performing experiments to simulate mechanical damage on these wafers, with and without the PBO buffer layer, and then by performing wafer-level reliability tests on them. It is expected that if the wafers are damaged and the silicon nitride passivation layer is cracked, moisture will enter and travel into underlying devices, which will result in MIM capacitor failures.

EXPERIMENTAL

This polybenzoxazole (PBO) buffer layer investigated in this study is a positive tone, photosensitive material and contains the polyamide precursor, photoactive compounds, crosslinkers, and solvents. The photopackage in this system is sensitive to the typical broadband UV exposure between 350 and 465 nm. The PBO film was coated on 100 mm diameter GaAs <100> wafers, which are either bare or device-patterned GaAs wafers. The device wafers were fabricated using an InGaP/GaAs HBT technology utilizing various metals and dielectrics deposition and patterning process steps. The devices on the wafers, in addition to the HBT, also include MIM capacitors, with a 600Å PECVD Si_3N_4 capacitor dielectric.

For the InGa/GaAs HBT device wafers, the PBO was coated on top of the PECVD Si_3N_4 final passivation layer, exposed and developed. The PBO on the wafers was then cured, before using it as resist and hardmask during the etching of the Si_3N_4 to open the bonding pads and streets. The coating and develop steps were performed using a coater and developer track and the wafers were exposed in a stepper. The PBO cure step was performed in a oven, while the bondpad and street opening was performed using a plasma etch system. After etch, the wafers were processed through standard backside processing steps. Much of the analysis was performed using focused-ion beam scanning electron microscopy (FIB/SEM).

For mechanical damage simulation, the GaAs device wafers with and without PBO buffer layer were exposed to and were intentionally damaged by diamond particles suspended in water, with diameters ranging from 1μm to 15μm. Wafer-level reliability test was then performed by subjecting the wafers to a temperature of 126°C at 2 atm for 24 hours and high humidity in an autoclave system. The MIM capacitors on the wafers were tested for failures before and after the simulated damage and after autoclave test was performed. A total of about 770 MIM capacitors were tested for each particle diameter.

RESULTS AND DISCUSSION

A. *Process Flow Comparison*

One of the advantages of PBO is that it is photodefinable. Therefore, a single mask approach can be used to open the bonding pads and street [2],[3]. In this approach, the PBO is used as photoresist and hardmask during the etching of the underlying layer, which in this case is the PECVD silicon nitride final passivation layer. After this step, the PBO is left on the wafer surface to function as buffer layer and mechanical protection for the underlying devices. Figure 1 show the process flow comparison between a typical flow after PECVD Si_3N_4 passivation layer deposition, without and with the PBO buffer layer. As can be seen, there is minimal difference, if not a reduction, in number of process steps required and with no additional mask needed. Furthermore, minimal or no significant difference in tool set requirements exists, other than the need for a cure oven.

B. *PBO Process Development*

The PBO was coated on GaAs bare test wafers, in addition to InGaP/GaAs HBT device wafers. Figure 2 shows the spin-speed curve of the PBO material. As can be seen, the PBO can be coated over a wide range of thicknesses ranging from 6μm to 12μm, making it suitable for buffer layer applications. The PBO thickness is reduced after develop, in addition to after cure, which is typical for polymers. Figure 3 and 4 show the thickness and range data on bare GaAs wafers, normalized to the target thickness (as-coated), obtained over a long period of time. As can be seen, the thickness and uniformity of this PBO is very good.

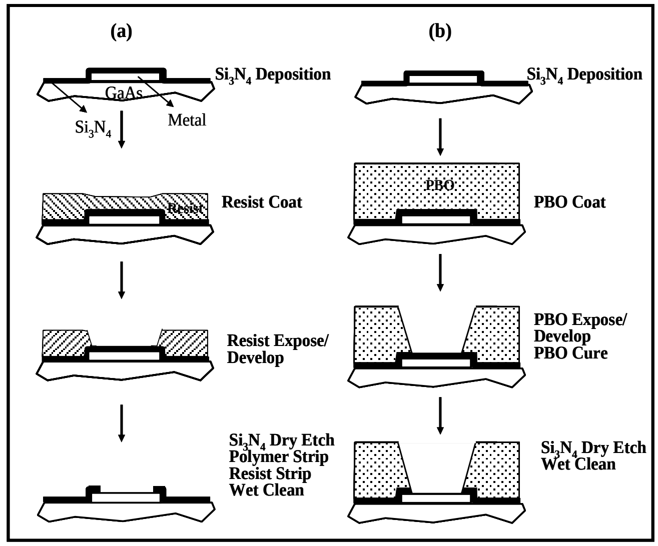

Fig. 1. Process flow comparison to open the bondpads between flow (a) without PBO and (b) with PBO as buffer layer.

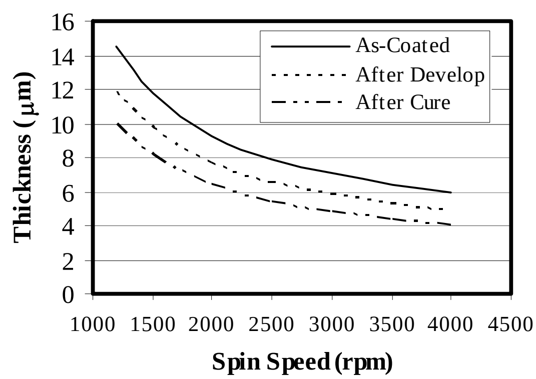

Fig. 2. Spin-speed curve of PBO for buffer layer, as-coated, after develop, and after cure.

After coating, the PBO is exposed and developed. Figure 5 shows the PBO on top of InGaP/GaAs HBT wafers in the street-to-bondpad area after street and bondpad opening etch, when exposed at various photo exposure conditions. As shown, the process has a large process window. Different sidewall PBO profiles can be obtained by changing the process conditions, depending on the product requirements.

Figure 6 shows the buffer layer critical dimension (CD) measurement data of a PBO process control monitor structure obtained after the develop step in production. The CD structure in this case, is much smaller than the size of the bondpad and street. Excellent CD results are obtained, which will easily meet the requirements for bondpad opening.

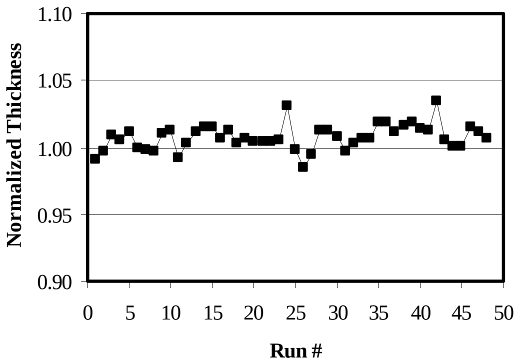

Fig. 3. PBO thickness data normalized to the target thickness, collected over three months.

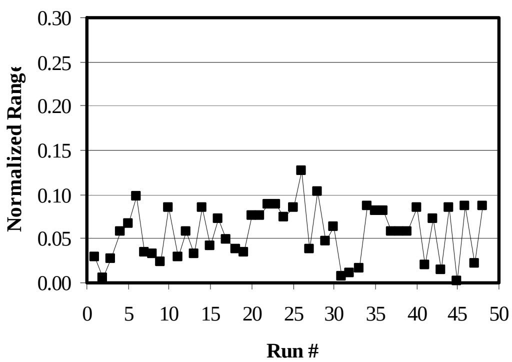

Fig. 4. PBO thickness range data normalized to the target thickness, collected over three months.

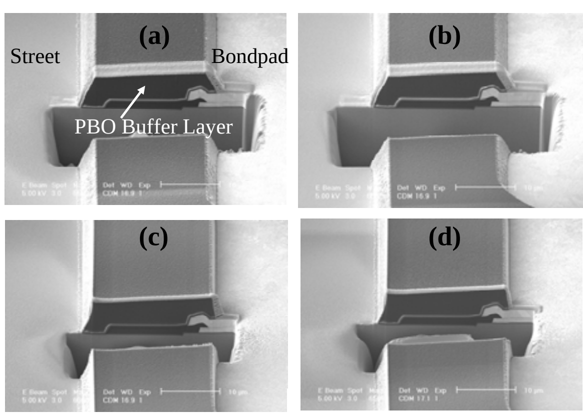

Fig. 5. FIB/SEM images of street-to-bondpad area, (a) to (b) obtained by changing the exposure energy by a total of 100mJ, and (c) and (d) obtained by changing the focus offset conditions used in (a) and (b) by a total of 3.0μm.

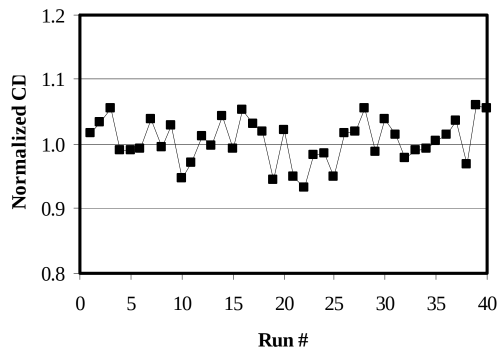

Fig. 6. The critical dimension (CD) data of a PBO process control monitor structure measured after develop, normalized to CD target.

C. PBO for Mechanical Protection/Buffer Layer

FIB/SEM analysis was performed on InGaP/GaAs HBT device wafers in order to evaluate the effectiveness of PBO as mechanical protection and buffer layer, protecting the underlying devices and interconnections. Figure 7 shows the InGaP/GaAs HBT device with and without the PBO buffer layer. As can be seen, the PBO coated the silicon nitride with excellent planarity, with no issues. The thickness of this buffer layer can be adjusted based on process and device requirements.

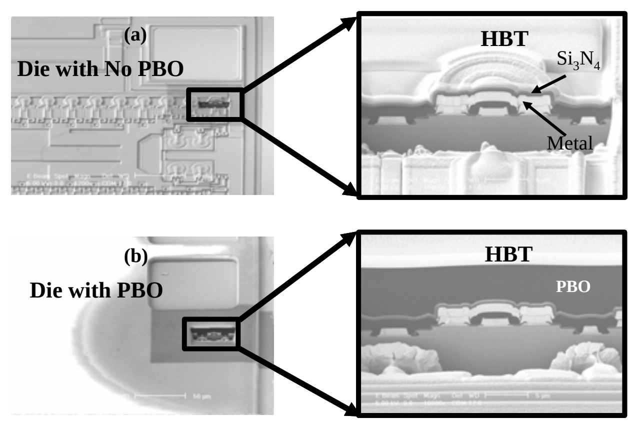

Fig. 7. FIB/SEM images of InGaP/GaAs HBT dies in the transistor area (a) without PBO and (b) with PBO as buffer layer.

Figure 8 shows the FIB/SEM and optical microscope images of mechanical damage observed on dies, with and without the PBO buffer layer. As can be seen from images of the wafers without the PBO, the silicon nitride passivation layer is cracked or damaged, and this damage extended down to the underlying devices and interconnections. This damage will then present a path for moisture to travel into the device, and which can result in device failures. However, with the PBO as mechanical protection, the damage is buffered and it does not extend all the way down to the passivation layer and the underlying devices.

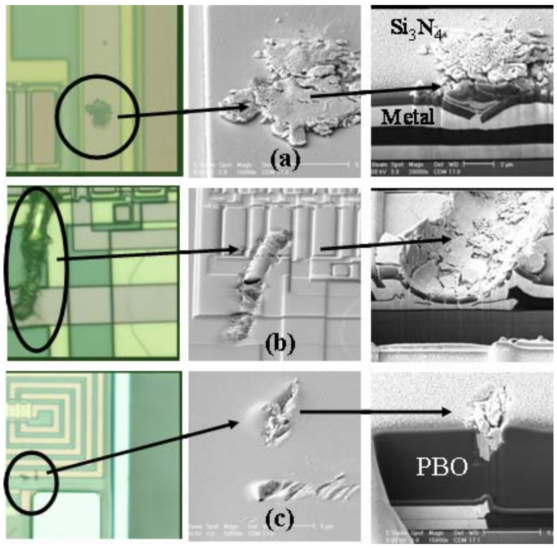

Fig. 8. Images of mechanical damage on top of InGaP/GaAs HBT wafers (a) and (b) with no PBO and (c) with PBO buffer layer.

D. *Wafer-Level Reliability of MIM Capacitors with PBO*

In order to investigate the effectiveness of PBO as mechanical protection and buffer layer, device wafers with MIM capacitors, with and without PBO were intentionally damaged by using diamond particles of different diameters. The wafers were then tested to see whether any MIM capacitor has failed or shorted because of the damage incurred. The wafers were then autoclaved for 24 hours, and then re-tested, to evaluate whether the extreme autoclave conditions will cause additional failures to the capacitors. Figure 9 shows the results from this experiment. As can be seen, there was minimal MIM capacitor failures observed before and after the damage was applied for smaller diameter diamond particles. As expected, more failures occurred for the wafers with no PBO buffer layer when the diamond particle size is larger (15μm). These results show that some small number of failures did occur after the intentional damage was applied on all wafers, which most likely were caused by diamond particles protruding directly on top of and damaging the MIM capacitors. However, by far, most of the MIM failures (117 failures out of 770 capacitors tested) occurred only on the wafer with no PBO buffer layer, and which was damaged by the largest diamond particle size (15μm) after autoclave. This indicates that the MIM capacitors were not damaged directly by the diamond particles and that the damage may not be located on or near the capacitors. Instead, the failure only occurred when the moisture entered through the damage or cracks in the silicon nitride layer, traveled and reached the underlying MIM capacitors during autoclave. These failures are detrimental and can present a significant and critical reliability problem. However, with PBO as buffer layer, there was minimal or no MIM capacitor failures observed after the autoclave test. The data shows that PBO is very effective in minimizing mechanical damage on wafers and is an effective buffer layer.

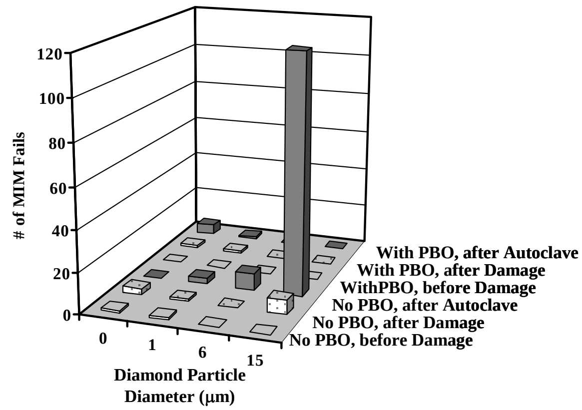

Fig. 9. The number of MIM capacitor failures observed on InGaP/GaAs HBT wafers with and without PBO buffer layer before and after the intentional damage was performed, and after 24 hours autoclave.

CONCLUSIONS

Photosensitive polybenzoxazole film has been used as buffer layer with excellent results. The film has excellent mechanical, electrical, and thermal characteristics and is suitable for InGaP/GaAs HBT technology. The PBO film has been shown to protect the underlying devices effectively and functions well as buffer layer, as evidenced by the simulated damage experiments performed using MIM capacitors. Additionally, the process is manufacturable, compatible to existing flow, and has no or minimal additional steps or stages.

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ACRONYMS

HBT: Heterojunction Bipolar Transistor
PBO: Polybenzoxazole