Photodefinable Polybenzoxazole Interlevel Dielectric for GaAs HBT Applications

Jiro Yota, Hoa Ly, Dragana Barone, Mike Sun, and Ravi Ramanathan

Skyworks Solutions, Inc.
GaAs Technology
2427 W. Hillcrest Dr., Newbury Park, CA 91320
Email: jiro.yota@skyworksinc.com

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Abstract

We have developed and characterized polybenzoxazole (PBO) as interlevel dielectric for GaAs heterojunction bipolar transistor (HBT) applications. The film is applied by spin-coating and is photosensitive and photodefinable. These characteristics allow the simplification of the process flow and allow the elimination of various steps, including resist coat, dry-etch and resist strip processes that are typically used to define the vias. Additionally, the film can be cured at lower temperature (250°C or higher) than the typical polyimide and the resulting film has good characteristics against moisture absorption and is stable thermally. Furthermore, the film has good planarity and gapfill characteristics, and has excellent mechanical properties. Results also show that device wafers fabricated with this film as interlevel dielectric, does not result in any significant difference in the electrical characteristics, when compared to those fabricated using dry-etch polyimide interlevel dielectric. All the above characteristics make this photodefinable PBO film to be well-suited as interlevel dielectric for and compatible with GaAs HBT processing. The use of this film will allow significant reduction in capital and consumable cost, in addition to reduction in cycle time of wafers manufactured using GaAs HBT technology.

INTRODUCTION

Polymer dielectrics have been widely used in the microelectronics industry for various applications, including interlevel dielectric, redistribution layer, final passivation, stress buffer layer, and as encapsulants in chip-scale and wafer-level packaging [1]-[7]. These polymers, including parylene, polyimide, benzocyclobutene (BCB), and polybenzoxazole (PBO), have many properties that are desired and required, including excellent dielectric, chemical, and mechanical characteristics [1]-[9].

Polybenzoxazole is a group of materials that is preferred and has become the polymer of choice for many thin-film applications recently [5],[10]. It has the advantage over other polymer films due to its functional group that does not have the polar carbonyl functional group (C=O), unlike polyimide films [5],[8]. The absence of carbonyl group in the PBO polymer prevents the formation of hydrogen bond between the polymer and water, therefore resulting in less water absorption in the film. Additionally, polybenzoxazole material is known for its excellent thermal stability and thermo-oxidative resistance [6],[10].

The PBO material is easily processed, and with a photosensitizer can be defined and patterned without any photoresist, in addition to being able to be used as hardmask during etching [10]. Furthermore, the developer that is typically used with this photosensitive PBO is tetramethyl ammonium hydroxide (TMAH) in water, an environmentally benign aqueous solution. Another added advantage of PBO is its relatively low curing temperature of $\geq$250°C, unlike many polyimides which have to be cured at 350°C or higher. This lower curing temperature is critical for most GaAs technologies, which thermal budget is limited and its processing temperatures mostly cannot be higher than 300°C. At high processing temperatures, the interface between the typical GaAs contact metals and the GaAs degrades, as Ga out-diffusion and the contact metal diffusing into the GaAs occur [5],[11]. All these make PBO to be well-suited for and compatible with most GaAs processing.

In GaAs technology, the typical films used for interlevel dielectric application include PECVD silicon nitride (Si_3N_4), polyimide, and benzocyclobutene (BCB). The PECVD Si_3N_4 is hard, conformal, and is excellent for protection against moisture absorption [12],[13]. However, it has a high dielectric constant (κ=7.0), cannot be used as gapfill material, and does not planarize the underlying structures and topography on the GaAs, and therefore makes multilevel metallization challenging. Even though polyimide can perform gapfill and its dielectric constant is low (κ=2.8-3.3), typically, the material has poor moisture absorption characteristics and has to be dry-etched, as with BCB. The photodefinable PBO, on the other hand, has similarly low dielectric constant (κ=2.9-3.2) and has lower moisture absorption property than polyimide [4],[10]. Additionally, it has better gapfill and planarizing capabilities than polyimide, which makes it attractive for GaAs applications, which typically have large topography. These include GaAs wafers manufactured with heterojunction bipolar transistor (HBT) technology which have significant topography due to the presence of various active and passive device and interconnect structures.

In this study, we have investigated and characterized the use of a photosensitive PBO film as an interlevel dielectric material for GaAs HBT technology. This photodefinable film allows the via patterning process to be performed without any photoresist coat, dry-etch, and resist strip process steps, which results in the significant simplification of the process flow, and therefore reduces both capital and consumable costs, and decreases the process cycle time.

EXPERIMENTAL

The interlevel dielectric film investigated in this study is a polybenzoxazole (PBO) material manufactured by HD

MicroSystems. This PBO film is a positive tone, photosensitive material and comprises the precursor, which is a polyamide, photoactive compounds and crosslinkers, in addition to solvents of propylene glycol monomethyl ether acetate and 4-butyrolactone. 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. The wafers are either bare GaAs wafers, or GaAs HBT device-patterned wafers. The GaAs devices, including the heterojunction bipolar transistors and other active and passive devices, and interconnections were fabricated using a GaAs HBT technology utilizing various metals and dielectrics deposition and patterning process steps. For the device wafers, the interlevel dielectric application process was performed by spin-coating the PBO (as-coated thickness of 3.3μm and post-cure thickness of 2.5μm) on the underlying metal interconnect (with a metal stack thickness of 1μm). The vias were then patterned by exposing and developing the PBO without the use of photoresist, and with no dry-etch and resist strip processes. The develop process step was performed in tetramethyl ammonium hydroxide (TMAH), after which curing of the PBO was performed in a convection furnace at 285°C for 45 min. After cure, wet HCl clean and/or short oxygen plasma ash can be performed, if needed.

Multiple material analysis were performed in order to characterize the PBO film on the GaAs wafers. Fourier Transfer infrared (FTIR) analysis was performed using Shimazu FTIR-8300 system to evaluate the cyclization of the PBO films before and after cure. The glass transition temperature (Tg) and the coefficient of thermal expansion (CTE) was obtained by thermo-mechanical analysis of the films using a Seiko TM/SS6000. The elongation, Young's modulus, and tensile strength was obtained using an Autograph AGS-100N, while the stress of the film was measured using a Tencor P2.

Focused-ion beam scanning electron microscope (FIB/SEM) analysis was performed using a FEI 820 dual beam system to evaluate the gapfill capability and profile of the PBO film and the via on top of the metal interconnections. Electrical characterization is performed by evaluating the resistance of 3.0μm vias. The results were compared to the results that were obtained from GaAs wafers that were fabricated using a typical GaAs process flow using polyimide as interlevel dielectric. Additionally, curing of PBO in other conditions with temperature ranging from 225°C to 300°C and curing time ranging from 45 min to 60 min was performed to evaluate and characterize the material properties of PBO.

RESULTS AND DISCUSSION

A. *FTIR Analysis*

One of the advantages of PBO is that it can be cured at lower temperature than a typical polyimide in order to achieve its desired properties. A typical polyimide needs to be cured at 350°C before the material is completely imidized. The PBO, which is cyclicized, can be cured at 250°C to achieve complete cyclization. Figure 1 shows the FTIR spectra of polybenzoxazole film on GaAs wafers before cure and after cure at various conditions. The spectra show the changes occurring with the C-N and C=O stretching peaks at 1539 cm^{-1} and 1651 cm^{-1}, respectively. As the cyclization progresses, the C-N and C=O peak heights become smaller until they completely disappear after curing at 250°C for 60 min. No changes in the spectra can be seen of the PBO film when cured at higher temperatures (45 min at 285°C or 60 min at 300°C). The complete cyclization of this PBO at lower temperature compared to polyimide, makes this material to be better-suited and more compatible with GaAs processing, and will yield in additional processing thermal budget and result in lower moisture absorption in the film.

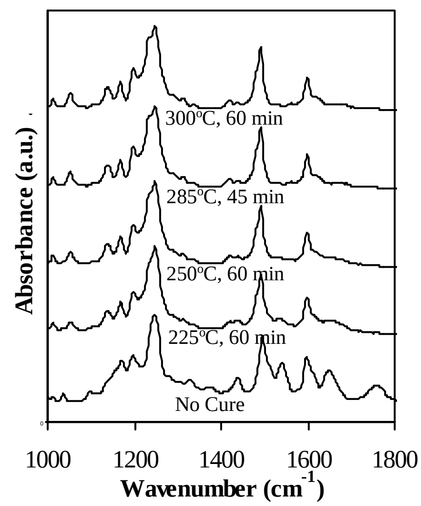

Fig. 1. FTIR spectra of PBO before and after cured at various conditions.

B. *Mechanical Characteristics*

The PBO was evaluated for its mechanical characteristics at different curing conditions. Table 1 shows some selected mechanical properties of PBO when cured at 250°C for 60 min and at 285°C for 45 min. As can be seen, there are some differences in mechanical property of the film between these two curing conditions. The curing condition can be selected based on the mechanical and thermal property requirements for the technology used. The data show that the polybenzoxazole film has good mechanical characteristics after curing at these relatively low temperatures that makes it well-suited for GaAs interlevel dielectric application.

TABLE I.
SELECTED MECHANICAL PROPERTIES OF CURED POLYBENZOXAZOLE FILM

Property	Cured at 250°C for 60 min	Cured at 285°C for 45 min
Tensile Strength (MPa)	120	122
Tg (°C)	257	280
CTE (ppm/K)	97	72
Elongation (%)	17	10
Young's Modulus (GPa)	2.2	1.9
Stress (MPa)	29	30

C. Process Flow and Characterization

Figure 2 compares the process flow of a photodefinable polybenzoxazole film as interlevel dielectric and that of a typical polyimide used in GaAs HBT technology. As can be seen the PBO process flow is significantly much more simple than the polyimide process flow. It also reduces the polyimide flow by at least 3 process steps, depending on whether any ash or clean is required after the cure step.

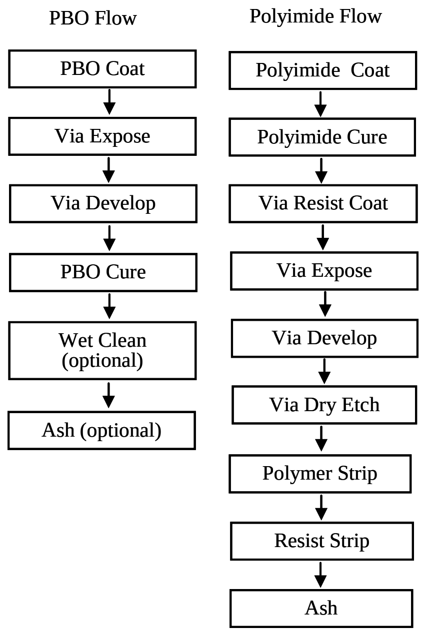

Fig. 2. Comparison between PBO and polyimide interlevel dielectric process flows.

Figure 3 shows the spin speed curve of the PBO. As can be seen, the PBO can be coated over a wide range of thickness, ranging from 3μm to 8μm, making it suitable as interlevel dielectric for GaAs processing, which could have metal thickness ranging from 1μm to 6μm. The PBO thickness is reduced after develop, in addition to after cure, the latter as with polyimide.

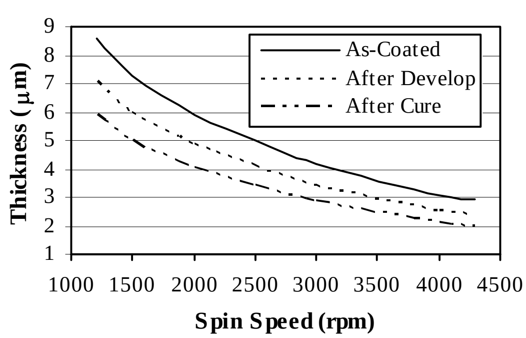

Fig. 3. Spin-speed curve of PBO as-coated, after develop, and after cure.

Figure 4 shows the profiles of 3.0μm vias on metal interconnect when PBO is coated with a thickness of a 2.5μm (after cure), and opened with the exposure energy and focus conditions varying from 500 to 800mJ and –3.0 to +1.0μm. The window for this photo process is large, and different via sidewall profiles can be obtained by changing the conditions. Since there is no dry-etching needed to pattern the vias, there will not be any over-etching concerns. Furthermore, any overexposure resulting in larger vias may not result in significant problem, as the bottom of the vias is defined by the silicon nitride via (defined during the capacitor patterning, performed at an earlier step). After cure, in some cases, a wet clean and/or an ashing step may be required, depending on the clean requirements for subsequent steps.

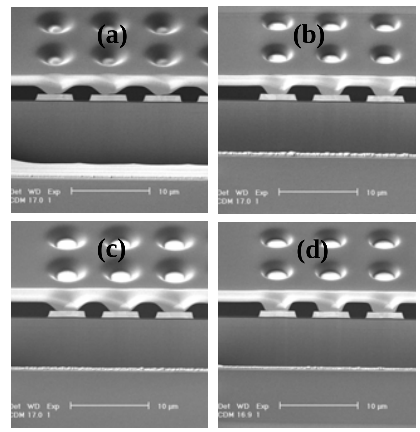

Fig 4. FIB/SEM images of 3.0μm vias with exposure energy/focus conditions of (a) 500mJ/-3.0μm, (b) 500mJ/+1.0μm, (c) 800mJ/-3.0μm, and (d) 800mJ/+1.0μm.

D. FIB/SEM Analysis

FIB/SEM analysis was performed on GaAs HBT device wafers in order to characterize the vias and interlevel dielectric. Figure 5 shows the FIB/SEM images of the vias on top of the heterojunction bipolar transistors, with the emitter, base, and collector region, of both PBO and polyimide as interlevel dielectric. The vias in this case are contacted to the emitter of the HBT. Figure 6 compares the bonding pad-to-street area of wafers with PBO and polyimide, while Figure 7 compares the region of vias on top of metal lines. As can be seen, there are no issues with opening small vias (on top of HBTs and metal lines) and large vias (in streets and bonding pads), with varying interlevel dielectric thicknesses. Good gapfill and planarity was observed, and no PBO residue was seen in the openings.

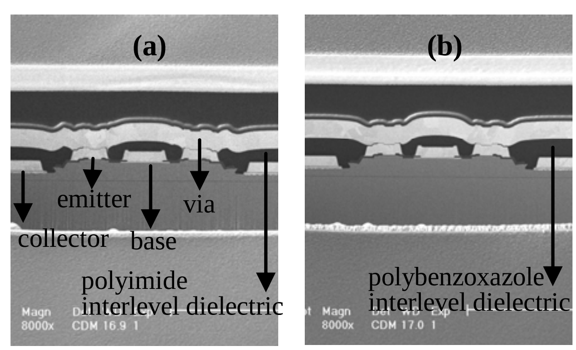

Fig. 5. FIB/SEM images of the HBT area with (a) polyimide and (b) PBO, as interlevel dielectric with the vias on top of the emitter.

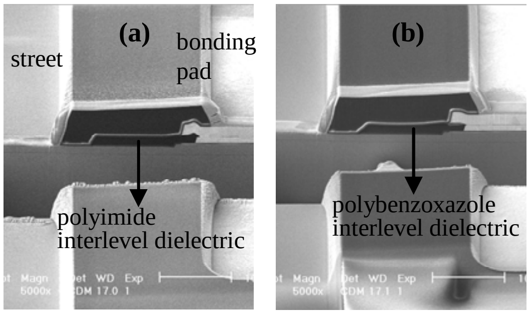

Fig. 6. FIB/SEM images of the bonding pad and street area with (a) polyimide and (b) PBO,as interlevel dielectric.

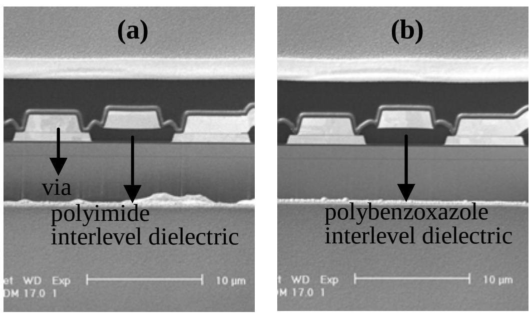

Fig. 7. FIB/SEM images of the vias on top of metal lines with (a) polyimide and (b) PBO, as interlevel dielectric.

E. *Electrical Characterization*

The resistance of the vias is evaluated in order to determine whether there is any difference electrically between the PBO and polyimide interlevel dielectrics. Figure 8 shows the resistance of 3.0µm vias as a function of the type of interlevel dielectric used. This via resistance is normalized against the mean of the via resistance with the polyimide as interlevel dielectric. As can be seen, there is no significant difference in via resistance with these two types of dielectrics.

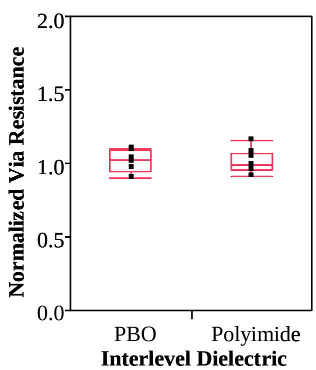

Fig. 8. Comparison of 3.0µm via resistance with PBO and polyimide as interlevel dielectric.

F. *Cost and Other Discussion*

As has been discussed earlier, the use of photosensitive PBO will allow the interlevel dielectric processing to be performed at lower temperature, when compared to polyimide. In addition, significant process flow simplification and reduction in process steps can be made. Consumable cost can be reduced, since no photoresist, resist stripper, dry-etch gases, and other chemicals are needed to pattern the vias. The only new material to be consumed is the PBO, which in this case, replaces the polyimide as interlevel dielectric. The elimination of the resist coat, dry-etch, resist strip, and possibly polymer strip and ash steps, will also significantly reduces the capital costs. This is especially significant when the tools used to perform the above processes are to be purchased, are new, and/or have not been fully depreciated yet. Furthermore, the elimination of at least 3 steps from the process flow will allow significant reduction in cycle time, which is critical in semiconductor manufacturing.

CONCLUSIONS

Photosensitive polybenzoxazole film has been used as interlevel dielectric for GaAs HBT applications. The results show that the film can be cured at lower temperature and has lower moisture absorption than polyimide. Furthermore, it has good mechanical properties and good gapfill and planarity characteristics. No significant difference in via resistance was observed of GaAs HBT wafers using this PBO as interlevel dielectric, when compared to polyimide. The use of this photodefinable PBO as interlevel dielectric will allow the elimination of multiple process steps, when compared to polyimide, and therefore, reducing the capital and consumable costs, and allow the cycle time to be decreased.

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ACRONYMS

HBT: Heterojunction Bipolar Transistor
PBO: Polybenzoxazole