Low Temperature Ion Beam Sputter Deposition of Amorphous Silicon Carbide for Wafer-Level Vacuum Sealing

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ABSTRACT

This paper presents a novel low temperature, wafer-level vacuum sealing method that uses line-of-sight deposition of amorphous SiC with ion beam sputter deposition. The ion beam sputter deposition system allows substrate tilting for off-normal deposition and operates with a pressure of approximately 3 X 10⁻⁶ torr during deposition. The amorphous SiC films have demonstrated compressive intrinsic stresses for growth rates between 0.06 - 0.13 nm/min. Test scaffold structures were fabricated by etching holes and trenches into bare Si wafers. The topography of sealing films deposited on the test scaffold structures shows that the film growth is directional with no visible down-hole deposition. The termination of the seal and the chemical resistance of the sealing films have been confirmed with a hot KOH immersion experiment.

INTRODUCTION

Silicon carbide (SiC) is currently being developed as a platform material for micro-scale devices that operate in harsh environments [1, 2, 3]. The chemical inertness and electrical and mechanical properties of SiC in harsh environments overcome the limitations of traditional silicon-based platforms [4]. The development of robust SiC devices requires encapsulation techniques that are compatible with the thermal budget and operation environment. Device encapsulation enables protection during assembly, reliable operation, and longer operation lifetimes. In addition, encapsulation in vacuum can improve the performance of resonant devices by reducing squeeze-film damping which leads to high Q-factors and improved sensitivities [5, 6].

Vacuum encapsulation typically involves either the bonding of a separate cap wafer or deposition of a sealing film to make a hermetic cavity. Several groups have developed wafer bonding methods for vacuum packaging of micro-scale devices [6, 7, 8]. Recent advances in these processes have enabled localized heating, preventing high temperature exposure to the active device area [8]. However, the use of wafer bonding leads to increased die sizes and higher costs. As an alternative to wafer bonding, several groups have developed encapsulation techniques that utilize thin sealing films deposited on porous scaffold films upon removal of sacrificial material [9, 5, 10]. This approach is attractive due to the integration of the film deposition with device fabrication and a reduction in the die size. Chemical vapor deposition (CVD) is the method typically used to deposit sealing films. The drawback to CVD sealing is that the film topography is conformal, causing deposition on the underlying structures, which leads to mass loading of the device. Other vacuum sealing methods, such as welding or solder sealing of electroplated scaffold structures [11] and reflow of thin films for sealing [12] have also been investigated.

This paper presents the first report of a low temperature, wafer-level vacuum sealing method that uses line-of-sight deposition of amorphous SiC with an ion beam sputter deposition technique. The implementation of ion beam sputtered SiC films for the encapsulation of released SiC devices is...
conceptually shown in Figure 1. After sacrificial material is removed through the cavities in the scaffold layer, a sealing film is directionally deposited for encapsulation. This approach is compatible with the SiC material platform due to the low deposition temperature (\(< 200\, ^\circ\text{C}\)) and the utilization of amorphous SiC as the sealing material which reduces the thermal mismatch between the SiC encapsulation films, SiC structural films, and SiC substrate. The vacuum pressure during the sealing film growth is on the order of \(10^{-6}\) torr, which is significantly lower than typical encapsulation pressures. This low pressure enables the line-of-sight deposition due to the higher mean free path and can dramatically improve the performance of resonant SiC devices.

**FABRICATION**

The amorphous SiC films were deposited with an ion beam sputter deposition system which is schematically shown in Figure 2. The system base pressure is approximately \(5 \times 10^{-8}\) Torr. A filamentless, radio frequency (RF) ion gun with a beam diameter of 16 cm is used to sputter the target material. To obtain a uniform deposition thickness across the substrate, a target with a relatively large diameter (25 cm) was selected. The substrate holder can be configured to hold 150 mm or 100 mm substrates and tilted. The tilting of the substrate holder allows the incident atoms to arrive at the substrate with an angle offset from the substrate normal. This offset angle is called the angle of incidence (\(\theta_i\)) and is defined as the angle between the incident atoms and the substrate normal. It should be noted that the ion beam sputter deposition system can be used to sputter various materials; however, this paper focuses on the deposition of amorphous SiC.

For this work, a SiC target with a Si-to-C ratio of 1:1 is sputtered with Ar ions. The beam energy and current of the ion gun are 1175 eV and 0.5 A, respectively. Rutherford Backscattering Spectrometry (RBS) analysis of films sputtered with these ion gun settings have produced films with a Si-to-C ratio of 1:1, which is expected for stoichiometric SiC. To obtain an amorphous structure, the substrate temperature is kept close to ambient during deposition; no substrate heating is used. Preliminary x-ray diffraction (XRD) analysis of the films showed no significant crystal peaks, which confirms that the films have an amorphous structure. The chamber pressure during operation is approximately \(3 \times 10^{-6}\) torr, which is relatively lower than conventional encapsulation pressures.

Thin films of amorphous SiC were deposited on unpatterned substrates for characterization of the deposition rate and film stress for various angles of incidence (\(0^\circ\), \(10^\circ\), \(20^\circ\), \(30^\circ\), and \(50^\circ\)). The substrates used in these experiments were bare 100 mm diameter Si (100) substrates. During deposition, the substrate holder is rotated at a speed of 5 rpm to obtain improved film thickness uniformity. A deposition time of approximately 1 hour was used to deposit the films.

Sealing films were deposited on patterned Si substrates for characterization of the sealing topography. Holes and trenches (0.8-2.0 \(\mu\text{m}\) wide) were etched into 100 mm diameter Si (100) substrates with deep reactive ion etching (DRIE) to be used as test scaffold structures (Figure 3). The sidewall roughening and scalloping shown in the SEM images is due to the cycling of etch and passivation steps during the DRIE process. The Si test scaffold structures were cleaned in pi-
RESULTS

The film growth rate and intrinsic stress have been investigated with thin films deposited on unpatterned substrates. The effect of the angle of incidence on the deposition rate and intrinsic film stress is shown in Figure 4. The film deposition rate was obtained through cross-sectional inspection of the films with scanning electron microscopy (SEM). A thin film stress measurement system (Tencor’s FLX-2320) was used to measure the curvature of the Si wafers before and after coating with 0.4 - 0.7 μm thick amorphous SiC films. The results show that the films are compressively stressed and the minimum stress magnitude obtained for the range of the angle of incidence used in these experiments is approximately 1250 MPa for an angle of incidence of 50°. The results also show that the film stress can be further reduced as the angle of incidence is increased; however, the trade-off is that the deposition rate is reduced. The magnitude of the intrinsic film stress can be further reduced by adjusting deposition parameters such as substrate temperature and gas flow rates, which is not the scope of this study. It should be noted that no delamination or cracks have been observed in the deposited films to date.

In addition to the film properties, the topography of the sealing films deposited on test scaffold structures has been investigated. Figure 5a shows the sealing film topography of a sealed hole. The deposition depth on the sidewall of the 0.85 μm wide hole is 0.7 μm. These dimensions are expected for an angle of incidence of 50°. Figure 5b shows the topography of a sputtered film onto etched trenches. The inspection of these structures with SEM shows no visible down-hole deposition.

To test the termination of the sealing and the chemical inertness of the SiC films, structures were exposed to hot (80 °C) potassium hydroxide (KOH) for 15 minutes. Cross sectional images of sealed and unsealed holes after the KOH test are shown in Figure 6a and Figure 6b, respectively. The KOH test of the sealed holes reveals no etching of the underlying silicon, confirming that the etch holes are completely sealed and the deposited films are pinhole free. In contrast, the films that were not sealed showed that the underlying Si was anisotropically etched.

CONCLUSIONS

A novel fabrication technique for depositing amorphous SiC sealing layers for vacuum encapsulation has been demonstrated. The results of the sealing topography confirm that the ion beam sputter deposition technique enables line-of-sight film growth. In addition, the chemical resistance of the films to hot KOH confirms the termination of the seal and the chemical inertness of the amorphous SiC films. Based on these studies it has been shown that this approach can be used to encapsulate released micro-scale devices on the wafer-level.

Further work is underway to fabricate sealed diaphragms to select the appropriate dimensions of the scaffold and seal-
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References


