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CVD diamond thin film technology for MEMS packaging

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Abstract

Due to its extreme hardness, chemical and mechanical stability, large band gap and highest thermal conductivity, poly-crystalline diamond (poly-C) is expected to be an excellent packaging material for biomedical and environmental MEMS devices. A poly-C thin film packaging technology has been developed to explore the application of this novel material on post-MEMS encapsulation packaging process. To study the poly-C thin film packaging a testchip was fabricated using PECVD deposited oxide as a sacrificial material. Large access ports were opened along the package edge to release thin film package using oxide etch. Then, additional poly-C growth was used to seal the access ports. In the test package, boron doped poly-C was also studied as the material for electrical feedthroughs that can be embedded into the undoped electrically insulating poly-C package. This poly-C thin film packaging process and the all-diamond packaging concept has been developed for the first time.

Keywords: Diamond; Thin film package; Integrated; MEMS

1. Introduction

MEMS packaging is a major challenge to microsystems industry. Although MEMS fabrication uses processes and tools borrowed from microelectronic industry with some modification, the MEMS design is quite different from its microelectronic counterpart because it is so application-specific that every specific device function plays an important role in the package design consideration. For example, resonant devices such as RF filter might require a vacuum packaging while accelerometers might work better at pressure that is close to atmospheric pressure. This makes the development of packaging standards for MEMS almost impossible. Therefore, packaging and package design must be closely coupled with the system and device design. The packaging process must be integrated into entire MEMS/microsystems fabrication process.

The MEMS packages are expected to provide MEMS devices and on-chip circuits with functions such as mechanical support, protection from environment, electrical interconnection and thermal management. Closely tied with the IC silicon-processing technology, MEMS packaging can take advantage of these mature chip-scale packaging techniques, including flip-chip and ball-grid-array techniques [1–3]. However, due to its diversity, MEMS packaging is still complicated. Recently, the developments in MEMS area have led to growing interests in MEMS packaging at wafer level to reduce the packaging and testing cost. Various approaches in this area can be sorted into two categories; integrated encapsulation process and wafer bonding process [4]. Integrated process adds extra steps, such as film deposition, patterning and etching into MEMS fabrication process to build micro encapsulation to protect MEMS structures. Typical examples are an epitaxial silicon cap to seal microstructures [5] and a silicon nitride shell to seal mechanical resonator for wireless communication applications [6]. Wafer bonding process uses different bonding methods such as fusion bonding, anodic bonding and eutectic bonding to encapsulate microstructures by using a second substrate of silicon, glass or other materials [7]. Recently, a unique approach of MEMS packaging by localized heating and bonding was proposed [8], to explore a versatile process of MEMS packaging at wafer level.

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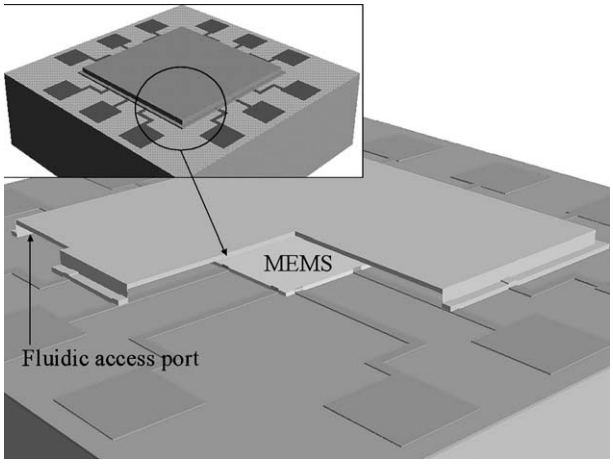

Fig. 1. Basic concept and cross section view of poly-C thin-film package.

In addition to developing and improving conventional MEMS packaging technologies, there is also a tremendous need for exploring new packaging materials for MEMS, especially for harsh environment applications. Due to its excellent mechanical, chemical, electrical and thermal properties, chemical vapor deposited (CVD) polycrystalline diamond (poly-C) has emerged as a novel material for MEMS applications, both for micro devices and packaging. Poly-C is an extremely inert material and is highly resistant to chemical attack. It offers protection against corrosive environments in which environmental MEMS devices are used. The mechanical strength of poly-C also makes it an excellent candidate for MEMS packaging. Its resistance to package deformation is especially useful for thin film packaging applications. Recently, the fabrication of free-standing diamond structures using Si molds [9], IC-compatible technique [10] and diamond-on-silicon micro acceleration sensors [11] have been reported. To apply the poly-C MEMS technology in packaging, in addition to thermal management application as heat sink [12], a fabrication technology of all-diamond packaging panel with built-in interconnects (boron-doped poly-C) was reported [13]. This paper reports, for the first time, the development of poly-C thin film packaging technology which is integrated into the post-MEMS encapsulation process. Boron-doped poly-C is studied as a material for feedthroughs, which is embedded in undoped insulating poly-C package.

Table 1
Comparison of different seeding methods

Seeding method	DPR	EP bias/ultrasonic	DW spin
Diamond particle size	100 nm	50 nm	25 nm
Carrier solution	Photoresist	Isopropanol	Deionized (DI) water
Substrate	Dielectric and metal	Conductive	Hydrophilic surface
Seeding density	$10^8 \sim 10^9$ cm^{-2}	$\sim 10^{10}$ cm^{-2}	$10^8 \sim 10^{10}$ cm^{-2}

2. Experimental procedure

A diamond thin film package for MEMS devices, depicted in Fig. 1, is fabricated using a 3-mask process. As shown in Fig. 2, this poly-C thin film fabrication process is designed to fit into post-MEMS fabrication. After MEMS device is fabricated, 0.5-μm thick feedthroughs were deposited and patterned using boron-doped poly-C. Then, a 4.2-μm thick PECVD oxide was deposited and patterned as a sacrificial layer used to release the package. This layer also serves as a protection layer for the feedthroughs and MEMS devices during the subsequent undoped poly-C growth. After the testchip was pretreated with diamond seeds, a uniform poly-C film with a thickness of 4-μm was deposited. The undoped poly-C package layer with large fluidic access ports is patterned using dry etching. The titanium layer serves as a pattern transfer mask. After the sacrificial PECVD oxide is removed, the package is sealed by closing the access ports through additional poly-C growth, which will only grow on existing poly-C layers.

A typical poly-C film fabrication process includes seeding, growth and patterning. Seeding is a pretreatment step to generate diamond nuclei before diamond growth begins. Currently, three different kinds of seeding methods, diamond-loaded photoresist (DPR) [10], diamond-loaded water (DW) and electrophoresis (EP) [14], are being used in the MANTL Lab at Michigan State University. A compar-

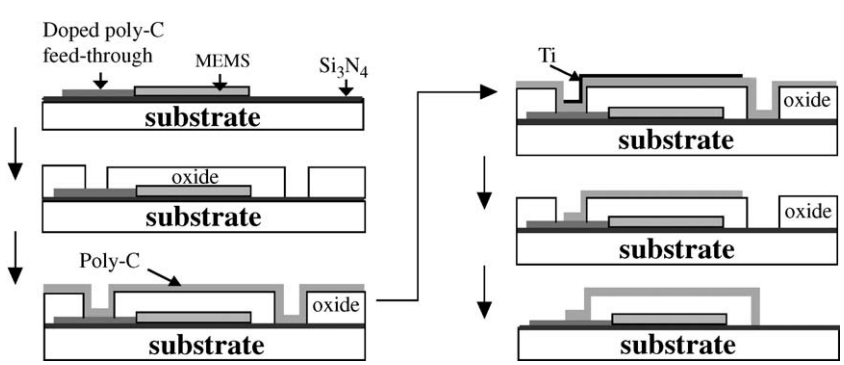

Fig. 2. Poly-C thin-film package fabrication process.

Table 2
Comparison of different diamond dry etching techniques

Dry etching technique	Gas flow (sccm)	Pressure (mTorr)	Ion energy/bias	Etch rate (nm/min)
RIE	O_2 (80) or	65	400 eV	35–40
	H_2 (80)			30–33
Xe^+ ion-beam	NO_2	0.2	2000 eV	200
ECR	O_2 (55)	0.4	−150 V	20–170
MPCVD	H_2 (200)	3×10^4	−150 V	9.7
	Ar (10) : H_2 (150)		−150 V	16
	O_2 (5) : H_2 (105)		+150 V	12
Inductively coupled plasma	Ar (10) : O_2 (30)	5		228
ECR	Ar (8) : O_2 (28) : SF_6 (2)	5	−130 V	75

ison of these seeding methods is shown in Table 1. Diamond seeding has no effect on MEMS devices which are protected by the sacrificial PECVD oxide. The seeding density of diamond particles (Table 2) is high enough to produce a uniform and pinhole-free poly-C thin film (Fig. 3(a)), to ensure the hermiticity of the package.

A poly-C thin film was grown using Microwave Plasma CVD (MPCVD) system in a CH_4:H_2 (1.5 sccm : 100 sccm) gas mixture environment with 40 Torr pressure at a temperature of 730 °C. The surface topography of a poly-C sample is shown in Fig. 3(a). The Raman spectrum, depicted in Fig. 3(b), shows a sharp diamond (sp^3 carbon-carbon bonding) peak at 1332 cm^{-1}, verifying a good diamond quality. As for boron doping of poly-C, poly-C layer was grown and in situ doped with tri-methyl-boron (TMB) diluted in hydrogen (0.098%). This doping technique leads to resistivities in the range of 0.003–0.31 Ω-cm [13]. The resistivity of doped poly-C film varies with doping level (TMB concentration) and deposition conditions. Although higher doping levels lead to lower resistivities, it sacrifices poly-C film quality.

Due to its chemical inertness, it is not possible to pattern poly-C using wet etching techniques. Different dry etching techniques, including reactive ion etching (RIE) [15], ion beam milling [16], inductively coupled plasma (ICP) etching [17], electron-cyclotron resonance (ECR) etching [18] and MPCVD plasma etching [19] have been reported previously to pattern diamond (Table 2). In the current work, a microwave electron–cyclotron–resonance (ECR) RIE system was used to dry-etch the poly-C film using the parameters highlighted in Table 2. The ECR systems differ from other microwave systems in their capability of coupling microwave power to the plasma at a very low pressure of around 1 mTorr resulting in surface damage-free processing, high anisotropic etch rate and excellent uniformity.

3. Results and discussions

Fig. 4 shows the first generation of fabricated poly-C thin film package, with a size of 1.5 × 1.5 mm. Several large fluidic access ports were opened on this package, along the package border. Inset (a) is a closeup view of the package border. During the sacrificial oxide etching, a DI water rinse step was repeated every 20 min to remove small bubbles generated by etching reactions. The entire package was released in about 8 h. The poly-C thin film experienced slight tensile stress after release, since the coefficient of thermal expansion (CTE) of CVD poly-C is very close to the CTE of silicon substrate. Films with zero-strains can be fabricated by adjusting the growth conditions. The study of sealing access ports is shown in Fig. 4(c) and (d). During the sealing, another 4-μm thick poly-C will only grow on the areas consisting of poly-C. The edge effect will make the poly-C grow at the edge of access ports, and prevent reaction plasma from going inside package. The additional poly-C growth for package sealing will require temperature compatibility of MEMS

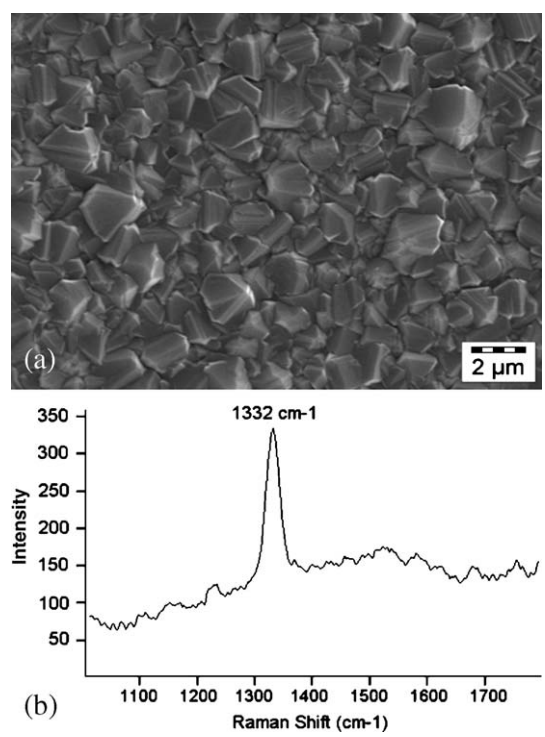

Fig. 3. (a) Poly-C film surface; (b) Raman spectrum of poly-C film.

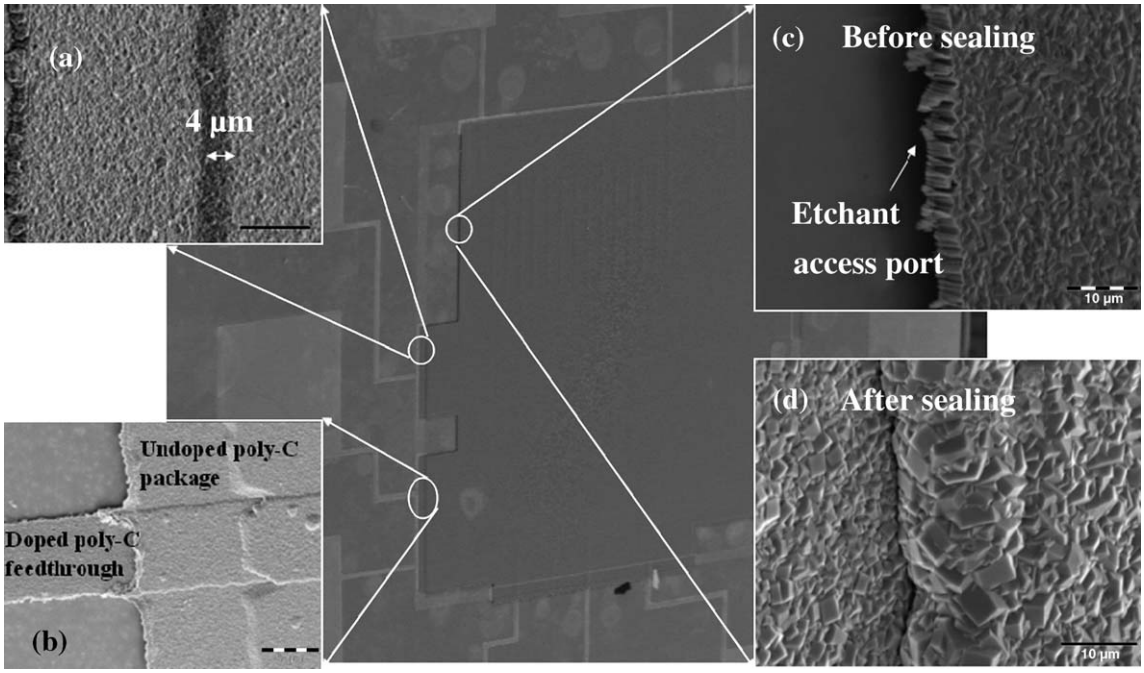

Fig. 4. Fabricated poly-C thin film package; insets are close view of (a) package border, (b) poly-C feedthrough and (c)–(d) Study of etchant access port.

device. The specific effects on MEMS functionality due to high-temperature processes are still being investigated. However, poly-C growth temperature can be lowered down to a temperature around 500 °C which is compatible with Si-MEMS process temperatures.

Resistivity study of doped poly-C layer has been conducted to explore the electrical property of doped poly-C. Since the gas doping is easy to control, the trimethyl-boron (TMB) gas diluted in hydrogen (0.098%) is used as the source of in-situ doping. An intensive study of boron-doped poly-C was conducted to find how resistivity of doped poly-C film varies with different TMB gas ratios, deposition temperatures and post-deposition anneals [20]. Usually, hydrogen-terminated CVD diamond film has a thin hydrogenated surface layer, which will become conductive after exposure to the atmosphere [21]. This hydrogenated conductive surface layer can be removed by a short-time dry etching. For the poly-C thin film package fabrication process, two advantages of using the same material (poly-C) for both feedthroughs and package are obvious. First, there will be no temperature compatibility concerns. Second, the feedthroughs will be embedded into the package after the package cap is fabricated to provide perfect sealing around the feedthroughs. Fig. 4(b) shows a fabricated poly-C feedthrough. A set of control samples with a 0.5-μm thick poly-C layer was prepared at 700 °C with different doping levels using the same deposition conditions for the feedthrough layer. The resistivity of the poly-C feedthrough film in the test package (Fig. 4) was 0.02 Ω-cm. The poly-C resistivities can be as low as 0.003 Ω-cm at high doping level (TMB : CH_4 = 0.5%). The resistivity of highly doped poly-C is comparable to that of poly-Si which is a common material for electrical interconnects. Additionally, the subsequent high temperature processing will have no effect on poly-C resistivity but could substantially affect the resistivity of poly-Si.

4. Conclusion

A poly-C thin film packaging technology, which can be integrated into post MEMS fabrication process, has been developed for MEMS applications. The first generation of package was fabricated, in which boron doped poly-C was used as an electrical feedthrough material while undoped poly-C was used as a structural material for the package. The poly-C packaging technology and all-diamond packaging are expected to provide new concepts in MEMS packaging for the first time. However, further work needs to be done in order to improve this technology. The optimization of package parameters according to current fabrication results and post-fabrication characterization of package, especially package diaphragm deflection, are being explored.

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