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Applications of fracture mechanics to quantitative accelerated life testing of plastic encapsulated microelectronics

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ABSTRACT

Accelerated testing must address the failure mechanisms active within the devices undergoing tests in order to assess lifetimes in a meaningful way. The assumption of constant temperature, thermally activated lifetime, based upon the Arrhenius assumptions, does not always provide the necessary understanding to interpret accelerated tests in microelectronics. Plastic encapsulants, dielectric polymers, and underfill materials are subject to delamination and cracking with thermal cycling. Crack propagation during use environment exposure, drives the potential for failure of microelectronic devices and is therefore a necessary focal point in qualification and life testing. This paper reviews the available research in the application of fracture mechanics to this class of problems in microelectronics including relevant test data. In addition, useful acceleration factor models are derived for polymer crack propagation based on principles of linear elastic fracture mechanics. Further, a simple approach to estimating the minimum temperature cycling ranges, necessary to propagate a crack, is also presented. Finally, a methodology of applying acceleration factors to develop testing plans is shown, with an example in spaceflight for a cubesat in low Earth orbit. Overall, this is a paper that shows a useful and appropriate process for creating physics of failure based life testing for delamination and cracking failures in microelectronic polymers in a temperature cycling environment.

1. Introduction

Polymers play a crucial role in enabling modern microelectronic devices, from encapsulating simple diodes to the most complex digital processors. Polymers are a mainstay of modern microelectronic packaging [1,2]. These materials perform the crucial function of providing structural enclosures that protect the active silicon element from the environment, while enabling handling and interconnection of the devices for assembly into functional circuits. The mechanical and dielectric properties of polymer materials, along with the range of economic options in processing, are what make them so important to the microelectronic industry. As shown in Fig. 1, an advanced device will encompass a number of layers of materials and interfaces within the structure. Adhesion and integrity of the polymer system is critical to the reliability of these devices [1]. Due to mismatches in properties and contact morphology these material interfaces are vulnerable to failure through delamination and crack growth under various loading patterns. The crack initiation and growth rate follows the theories of fracture mechanics which can be used to directly understand the durability of the system. These principles are subsequently explained along with useful applications to testing of microelectronic devices that depend on polymer packaging.

2. Function and properties of microelectronic polymers

The major classes of polymers used in microelectronic packaging include epoxies and polyimides. For many types of advanced devices, polyimides are applied, as a film, over the hard layers of inorganic passivation, as one of the last steps in fabrication of the wafer. This application provides for defense of the active circuits on the surface of the die, against subsequent handling. This enables packaging and allows for the assembly of the silicon device into useful products, similar to the structure shown in Fig. 1. In addition, polyimide provides for a barrier against moisture during handling, packaging and service. Polyimide films also reduce stresses imparted to the surface of the circuits by the surrounding encapsulations that make up the package structure. Variations in polymer chemistry which make up this class of polymer (polyimides) will not be discussed in detail, but it is important to note specific polymer compositions may have specific responses to loading and environment, given different thermal and mechanical

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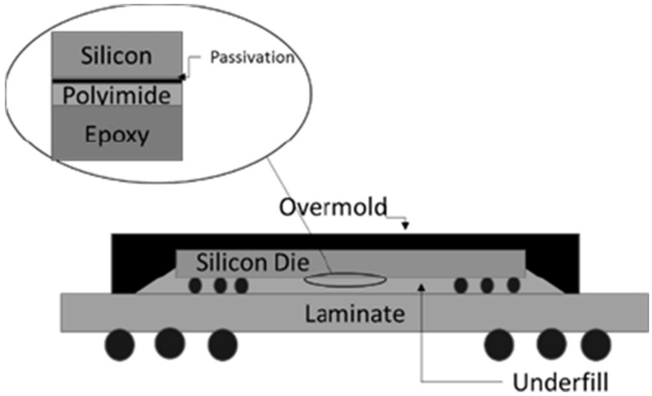

Fig. 1. Simplified schematic of over molded flip chip ball grid array. The inset shows typically layered structure on which the reliability of these devices depend.

properties that are a result of the chemical variations in the polymeric chains [2,3].

Polyimide chemistry can be made to be photoimageable. This combined with superior dielectric properties, and thermal stability, enable high yield processing that is key to cost effective advanced devices. Polyimide is preferred for advanced packaging applications such as the addition of solder bumps for flip chip. They are also used in many other types of devices including high voltage applications, PIN diodes and microelectromechanical systems (MEMS), owing to processability, mechanical and dielectric compatibility, and thermal stability.

Epoxies are also highly versatile and diverse in terms of composition, properties and processing, enabling their use for structural functions and final packaging or encapsulation. Epoxy based *adhesives* are used for structural bonding, including die attach for conventional wirebond devices, as well as underfill for advanced flip chip devices. Fig. 1 shows a typical high volume, high input-ouput (IO) pin count package schematic common in microelectronics. This is an example of an encapsulated device in which interface adhesion plays a critical role in the reliability of the device. There are many other devices types ranging from optocouplers to MEMS that depend on polymer integrity to ensure reliability.

Die bond applications for epoxy adhesives are well understood, as this has been a mainstay of packaging for many years. However, development of flip chip has driven the need for improvement in understanding of reliability considerations for epoxies used in underfill applications. In the case of adhesives, pre-formed solids or liquid applications are used. For advanced flip chip devices, underfills are often applied in liquid applications which depend on capillary action to fill the gap between the device and chip carrier [2]. Filling the gap reduces the opportunity for moisture to reach the active surface of the die and provides for the structural integrity that relieves plastic strain in the solder joints.

The properties of epoxy adhesives and liquids are modified with fillers to provide control of thermal expansion properties. A variety of particulate fillers can be used to control thermal expansion to more closely match other components in the package structure. This is the key to providing reduction and control of stress, given differences in thermal expansion between the die and the chip carrier. For many types of devices, printed circuit board laminates are preferred for cost considerations, but ceramics are also employed for specialty applications.

Fig. 2 shows a solder bump section revealing the adjacent underfill that is heavily loaded with particulate fillers for control of thermal expansion of the epoxy matrix. Fillers may also be used to impart electrical conductivity or to enhance thermal conductivity. These fillers also affect the mechanical behavior including fracture as the crack tip interacts with the particulates.

Epoxy *molding compounds* are most often used for final packaging of advanced devices but liquid applications are also used for a variety of

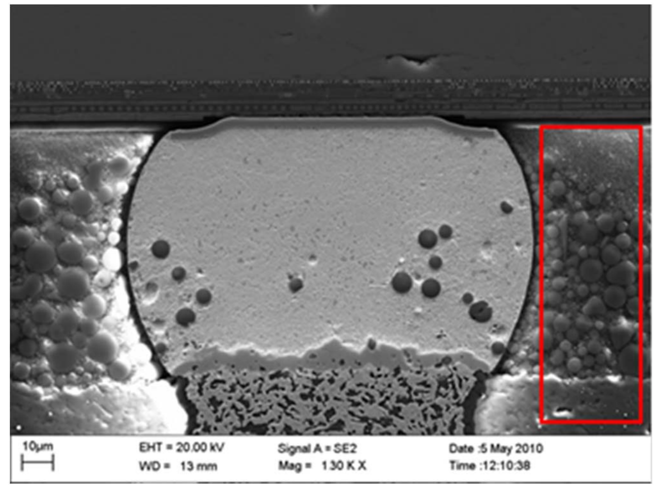

Fig. 2. Solder bump electron micrograph showing the bump and surrounding epoxy underfill. The inset shows the epoxy matrix heavily loaded with particulate fillers to control thermal expansion of the matrix.
(Photograph provided by J.O. Suh, NASA JPL.)

applications for final encapsulation (glob-top). Transfer molding is often used to facilitate rapid processing and yield. The composition of molding compounds or encapsulants can be substantially different from adhesives, but fillers are also commonly used to control their properties.

3. Failures in polymer packaging

The system of materials in the realm of modern polymer encapsulated packages creates complex multilayer structures. The reliability and lifetime for these devices depends on the integrity of these multilayer polymer structures. However, failures and defects can and do occur in application and testing.

Delamination or failure of a bonded interface is a primary failure mechanism of packaged structures. Therefore, adhesion of the layers in structure is critical to the reliability of many classes of semiconductor devices. *Delamination precedes other failure mechanisms in microelectronic devices*, which activate as a result of loss of the functions that polymers provide in the devices. Delamination will generally mean a loss of the dielectric or electrical insulating function, loss of structural integrity and stress control and a loss of the moisture barrier. Hence, for flip chip devices, delamination precedes corrosion of circuit elements and fatigue of the solder bumps [1,4,5]. An example of failure of underfill in an unencapsulated flip chip device, assembled to a ceramic substrate and employing an epoxy underfill, is shown in Fig. 3. The micrograph prominently shows the fillet loss. However, the propagation of the crack along the epoxy to chip carrier interface in this device is of greater

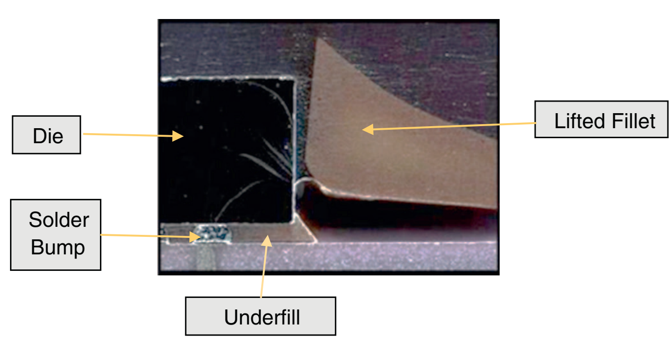

Fig. 3. Unencapsulated flip chip structure with failed underfill.
(Photograph provided by Scott Popelar, Cobham Semiconductor Solutions (formerly Aeroflex)).