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Acoustic detection of micro-cracks in small electronic devices

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ABSTRACT

We demonstrate the feasibility of in-situ acoustic detection of micro-cracks in small electronic devices. Applying precisely controlled damage to test vehicles using a nanoindenter, we record brittle fracture of thin layers by means of an ultra-sound piezo sensor, which is able to detect micro-cracks in the moment they emerge. This robustness test does not require further preparation effort that may induce additional stress to a sample or modify it physically, inhibiting unambiguous failure analysis. With regard to its applicability and limitations, we put acoustic emission into context with standard ex-situ experimental procedures for crack characterization in micro-electronic structures.

1. Introduction

The continuous trend towards smaller dimensions in densely packed micro-electronic devices goes in hand with increased challenges for device reliability. In particular, any gain in size and efficiency occurs at the expense of mechanical stability when new materials (e.g. low-k dielectrics) are introduced. Already in production, during probing (electrical functionality test) and wire bonding, this directly reflects in an increased risk of cracking in oxide layers embedded in back-end of line (BEOL) pad stacks. Once an oxide crack is present and propagates during device operation under external stress, metal may migrate into. In many cases this eventually leads to electrical failure. Similarly, intrinsic mechanical stress, arising from a mismatch of the coefficients of thermal expansion (CTE) at interfaces or from temperature gradients, tends to lower mechanical stack robustness and to cause delamination.

In order to predict and improve the mechanical stability and, thus, to increase the reliability of micro-electronic devices, suitable fast-forward robustness test procedures such as *in-situ* crack detection are essential. By contrast, most of the existing standard methods for crack detection, such as chemical decoration of cracks, cross-sectioning or FIB-cutting, X-ray, Scanning Acoustic Microscopy (SAM), etc., allow detecting cracks only after the fact. Then, however, mapping the failure image to the history of stress applied to the sample prior to analysis is practically impossible. Moreover, these methods require further preparation effort, during which additional damage or mechanical stress is introduced to a sample. Any invasive or even destructive preparation, in turn, will complicate a distinct analysis of device failure.

In this paper we demonstrate the feasibility of in-situ crack detection via acoustic emission as a fast-forward robustness testing method for small electronic devices. This method is based on the sudden release of elastic energy in terms of elastic stress waves. Mounting a sample on top of an ultra-sound sensor and damaging it in a precisely controlled way by means of a nanoindenter [1,2,7,8], we detect brittle fracture in thin film test vehicles and BEOL pad stacks upon emergence. This technique of damage evaluation is novel in semiconductor industry to common knowledge and first results have been reported only recently [3]. It enables a better understanding of the damage behaviour and critical load threshold in IC chip bond pad stacks, in that it allows a straight-forward validation of simulation models. At the same time, it has the potential to significantly reduce the effort of post-testing failure analysis, in particular with respect to sample sizes.

2. Experimental setup and work flow

Our setup consists of an Agilent G200 nanoindenter and a Vallen piezo-electric acoustic sensor inside a customized holder. The sensor is sensitive to a frequency range of 100–300 kHz, which is known to be sufficient for detecting brittle cracking in a wide range of applications. The chip sample is mounted on top of the sensor by means of a viscous couplant adhesive, e.g. honey [4] in order to enable sufficient transmission of ultrasound. During surface penetration by means of a rounded indenter tip, both the load–depth curve and the acoustic signal peak amplitude (APK) and average

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(ASL) are continuously recorded (see e.g. Fig. 1). In the event of a crack, the load–depth curve exhibits a characteristic kink (pop-in), and a distinctive peak above the noise threshold is found in the APK signal. Both these events are time-correlated and characteristic for brittle fracture. After detection of a cracking event, indentation is stopped automatically, and the sample undergoes failure analysis in order to verify the damage by optical means. The so-obtained failure image is then correlated to the obtained indentation data.

3. Results overview

In order to characterize acoustic emission as method for crack detection and to demonstrate its feasibility, we first focus on simple test vehicles, that is, thin mono-material films deposited on top of a Si substrate. In doing so, we focus on standard materials that are widely employed in semiconductor fabrication processes. While this elementary approach allows most insight and allows best to calibrate the method, we point out in addition the applicability of the method to product level. To this end, we present acoustic emission data from measurements done on a BEOL pad stack of a test chip, together with the corresponding failure image.

3.1. Thin Si_3N_4 film

In Fig. 1 we present load–displacement and acoustic emission data obtained from nanoindentation on a thin Si_3N_4 film on top of a Si wafer. Prior to this experiment, the Si_3N_4 elastic modulus and indentation hardness were measured as $E = 180 \pm 8$ GPa and $H = 20 \pm 2$ GPa, respectively, using a Vickers indenter tip. Our results fit well into the range values reported for thin layers [5] and indicate the brittleness of our Si_3N_4 film. Accordingly we observe clear indication of fracture beyond a critical load applied to the sample by a rounded-tip indenter of radius 10 μm. In Fig. 1 the amplitude channel of the signal recorded by the acoustic sensor exhibits a distinct peak at a load of 115 mN which synchronizes with a pop-in visible in the load–displacement curve. In Fig. 2 the corresponding half-penny radial crack emerging from the imprint in the Si_3N_4 film is recovered. This behavior is typical for spherical cracking in brittle material films [6].

3.2. Thin SiCOH films

Indentation on a thin SiCOH film on Si substrate allowed qualitative correlation of the observed failure images (Fig. 3) with the critical loads required for cracking and the acoustic signal amplitudes (Fig. 4). As one would have expected, indentation with a rounded tip of radius 5 μm requires less load and causes less damage in the thin film as compared to the case where a larger rounded tip of radius 10 μm is used. Notably, both the dimensions of the damage (circle diameter) and the cracking loads scale with approximately a factor of 2. At the same time the acoustic signal amplitude is not doubled but still larger by ca. 0.25 V in the case where the larger tip is used. It should be noted here that our sensor does not capture the high-frequency signal components (larger than 500 kHz) signal due to its limited frequency bandwidth.

The failure images depicted in Fig. 3 shows radial cracking of the SiCOH film and spalling of small pieces in concentric rings around the position of the indenter. Moreover, cracks are found in the Si substrate. While a valid simulation model would be required for better understanding, an intuitive modelling approach done elsewhere for a comparable indenter experiment [6] provides some insight: up to a critical indenter load, the material around the indenter imprint gets deformed elastic-plastically and experiences buckling, similarly to a bending plate. At the same time the thin film delaminates completely from the Si substrate, as indicated by the smooth Si surface observed in Fig. 3. Beyond the critical load, the SiCOH cracks around the indenter tip and gets partially spalled out of the indent "crater", while some plastically deformed residual material remains in the center, held down by the indenter tip.

We have measured Young's modulus and hardness of the SiCOH film as $E = 60 \pm 5$ GPa and $H = 7.0 \pm 0.5$ GPa. This small hardness and higher elastic deformability as compared to e.g. brittle Si_1C_1 or Si_3N_4 are due to the fact that, during film deposition, H_2O_2 was used as a pre-cursor, causing the film to be soft. For the same reason, in semiconductor fabrication, SiCOH is widely employed in order to increase stack deformability and, thus, to reduce the risk of material cracking.

3.3. Test chip pad metallization

We now demonstrate how crack detection via acoustic emission can be applied to the case of a test chip with an AlCu pad metallization of thickness 2.8 μm. In Fig. 5 the indenter and acoustic signal data indicate a crack in the pad stack at an indentation depth of ca. 3 μm, which corresponds to the position of an oxide layer underneath the pad. At smaller depths, no cracking is to be expected as the indenter tip simply penetrates and plastically deforms the ductile metal by means of material pile-up around the indenter mark. Indeed, failure analysis by means of chemical etching of the pad metallization and optical microscopy reveals a crack in the said oxide layer, as predicted. This experiment could be reproduced on 50 pads with an acoustic crack detection rate of 100%.

4. Application to production workflows

Within the production workflow oxide cracking under pad constitutes a critical problem during electrical functionality testing (probing) and wire bonding. In this context our robustness test based on nanoindentation allows comparing the critical loads required to induce cracking for different BEOL pad stack architectures. A direct quantitative mapping to probe needle or bond capillary loads is not possible though unless a suitable correlation based on measurement data from probing and nanoindentation tests has been established. Still our robustness test method is well suitable as a fast qualitative disaster check with respect to probing and bonding.

Setting up the acoustic sensor inside a single needle probing tool for probe card calibration or comparison of stack robustness is only one further of many imaginable applications for crack

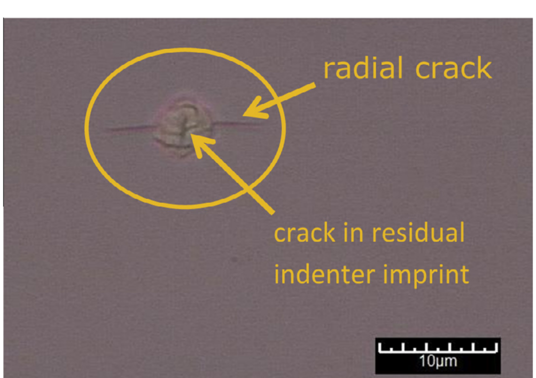

Fig. 1. Brittle cracking of a thin Si_3N_4 film (thickness 1 μm) on Si substrate upon nanoindentation: optical microscopy (1000×) of failure image related to measurement data presented in Fig. 2.