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An acoustic emission sensor system for thin layer crack detection

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ABSTRACT

We present a new method for semiconductor layer characterization enabling simultaneous crack generation and detection based on the established acoustic emission testing. In this paper, we explain the test concept and failure mechanism of diamond tip indentation with acoustic wave measurement on oxide layers by analytical modeling and computer-aided simulations. For this purpose, an innovative design of a sensor-indenter system was developed and experimentally verified. In further tests, the new acoustic crack detection method is correlated with proven optical inspection methods and the good reproducibility of the measurement is demonstrated. The high sensitivity and resolution of this method offer new opportunities for thin layer characterization at lower time and cost. The new high-efficient method can be used especially for process qualification for semiconductor wafer test, where oxide cracks can be induced by sharp probes causing electrical failure of the chip.

1. Introduction

At semiconductor wafer test chips are electrically tested for functionality and specification limits before further processing. Therefore, the I/O pads of chips are contacted by elastic springs (probes) to ensure an electrical connection between the device and a test system. To achieve a low electrical contact resistance between the probe and the pad a sufficiently high contact stress is required, but exceeding leads to an increased fracture probability of brittle insulating layers below the pad. This can cause a failure of the device due to short circuits or leakage [1, 2].

Proven methods for crack detection are the chemical-optical inspection, which is used in particular for CMOS technologies [1], and the more elaborate preparation of scanning electron microscopy (SEM) images of focused ion beam (FIB) prepared cross sections. Both methods are destructive, time-consuming, and thus cost-intensive. Moreover, compared to CMOS-technology devices with evenly spaced oxide-metal layers, the chemical etching method does not work for complex and vertical integrated structures, which are typical for power-technology devices.

Alternatively, we present a new method, based on the established acoustic emission testing, to detect mechanical cracks of silicon oxide layers during the contacting in real-time.

As the released energy of acoustic shock waves is extremely small a perfect coupling of the probe and the acoustic sensor is mandatory. For this a novel sensor-indenter system was developed and characterized to reach a high sensitivity of the acoustical signal.

The suitability of the new method is demonstrated on appropriate test structures. Even layer cracks in nano-scale dimensions are acoustically detected during contacting, which are almost invisible by optical inspections. This opens a new way for thin layer characterization of semiconductors.

2. Acoustic emission (AE) test method

During solid material fracturing the stored elastic energy is released suddenly by producing acoustic shock waves. The volume and surface waves propagate with ultrasonic frequencies (100 kHz–2 MHz) at low amplitude and short durations. For this purpose, high-sensitivity piezoelectric sensors are coupled (glued) on the surface of the body for acoustic wave transmission. In addition, low-noise amplifiers and high-resolution A/D converters are essential, in order to receive a sufficient high signal gain and quality [3].

For the crack experiments a customized test bench setup is used. The contact unit, glued on top of the piezoelectric sensor, is mounted in upright position on a 3-axis linear precision stage. A vertical low force sensor enables measurements with a resolution of ≤ 0.5 mN. The test structure is glued on its backside to a sample holder flipped over on a metal frame. During contacting, the indenter tip presses vertically to the surface of the test structure (see Fig. 1) and transmits the acoustic signal from the indenter to the piezo sensor. The time-synchronized signals for both the force and the piezo sensor are amplified and filtered by an A/D-controller unit. Data acquisition and further post-processing is done by a computer system.

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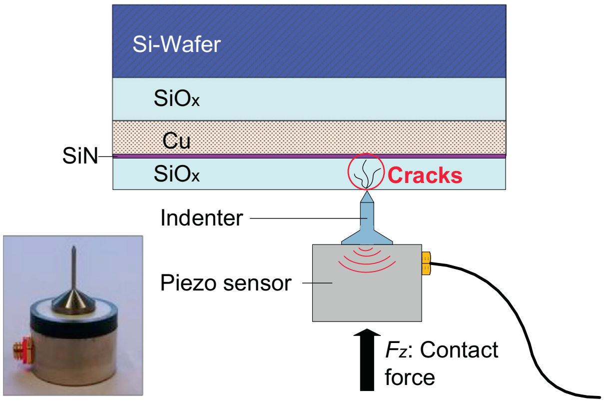

Fig. 1. Principle of acoustic crack detection.

2.1. Sensor-indenter system

The sensor-indenter system for acoustic wave detection consists of a cylindrical metal probe with a conical diamond tip at the upper end (i.e. indenter). The tip is pressed on the surface of test structures with increasing contact force (see Fig. 1). The lower, widened end of the indenter is glued on top of the sensor interface. Hence, the indenter serves both as a mechanical contactor for controlled crack generation and transmits the acoustic signal to the piezo element of the sensor.

In this study, all experiments are done by using indenters with flat 10 µm diamond tips. This tip diameter size is typically used for contact probes at semiconductor wafer test. For the acoustic measurements we use a resonant, piezoelectric sensor which has a high sensitivity over a broad frequency range (100 kHz … 900 kHz).

To achieve the highest sensitivity of the sensor-indenter system the geometry of the indenter was optimized analytically and by FEM-simulations and later verified in experiments.

The analytical model of the ideal indenter is similar to a one-sided fixed rod with a constant diameter (no transversal contraction), which is glued on the sensor surface with a free-ended tip. By a harmonic stimulation on the free side the rod gets into a longitudinal oscillation. The undamped resonance frequencies f_k of the indenter can be calculated by [4].

$$f_k = \frac{(2\,k - 1)\,c_l}{4\,l}, \tag{1}$$

where c_l is the longitudinal sound velocity of the material and l its free length. The parameter k ($k = 1, \ldots, n$) defines the order of the natural frequencies, which are calculated in Table 1 and shown as vertical lines in Fig. 2.

Before observation of the complete sensor-indenter system the frequency response characteristic of the separate piezo sensor was derived. This experiment was done using an emitter, which was pressed slightly on top of the sensor surface. The sinusoidal input signal of 1 V had a frequency bandwidth of 50 kHz to 1 MHz and a step size of 1 kHz.

During the next step, the indenter was glued on the surface of the piezo sensor. The sensor-indenter system was stimulated by an emitter, which was loaded by a vertical contact force of approx. 500 mN on the indenter tip, with the same frequency range as described before.

Fig. 2 shows the measured frequency response curves as a voltage signal in dB_{AE} (reference value 1 µV) of the piezo sensor (solid line) and the sensor-indenter system (dashed line) as a function of the excitation frequency. Compared to the frequency response of the piezo sensor only, which has a relatively flat frequency response, the sensor-indenter system shows several high maxima close to the natural frequencies of the indenter (see Table 1). This shows that the sensor-indenter system oscillates at its resonance frequencies in longitudinal mode after harmonic stimulation.

Table 1
Analytical resonance frequencies f_k ($k = 1, 2, \ldots, 5$) of a one-sided fixed steel rod ($c_l = 5100$ m/s) with 10 mm length l.

k	1	2	3	4	5
f_k (kHz)	128	382	637	893	1148

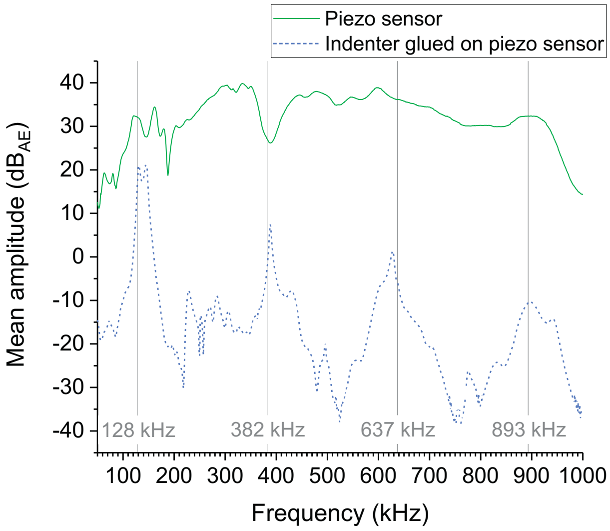

Fig. 2. Measured frequency response curves and analytical resonance frequencies (vertical lines).

Now it was possible to tune the first order of the eigenmodes of both the piezo sensor and the indenter to the exact same frequency. If the system is oscillating at the resonance frequency, the signal gain is at the maximum amplitude.

Later on, the sensor-indenter system was simulated by a 3D finite element method (FEM) model (see Fig. 3) to calculate the eigenmodes and frequencies of the components. Its resonance frequencies were tuned through design optimization of the indenter to achieve the highest sensitivity for the acoustic signal detection. In addition, instead of the previous 2-component solution (indenter and fixing ring, see Fig. 3 above) a 1-component solution (so-called monolithic indenter, see Fig. 3 bellow) was developed. The monolithic indenter design eliminates friction between the fixing ring and the indenter and enlarges the contact area between the indenter base and the sensor surface. Due to these design changes disturbances are minimized and the system sensitivity is increased by a better coupling.

Fig. 4 shows the simulated frequency response curves in dB_{AE} over the excitation frequency. Within a frequency range of 100 kHz … 500 kHz the amplitude is increased by approx. 10 dB_{AE} using the monolithic indenter.

2.2. Analytical model: crack initiation and detection

The conical-shaped diamond tips are flat on top (i.e. flat punch) with a rigid surface, which is pressed vertically on the surface of an elastic half space with the force F (see Fig. 5). The flat punch has a contact area of radius a and sharp edges ($r_{edge} = 0$). The contact area A between the indenter and the half space is assumed to be circular and equal to the indenter tip area. There is no friction considered between the contact pairs [5, 6]. Further assumptions are that the free surface outside the contact area has no normal stress σ_z acting on it and the displacement in z direction is consistent with the flat facet of the rigid punch [6].

As during indentation with a flat punch the contact area remains constant, the contact pressure linearly increases with the load. The mean contact pressure p_m over the contact area A is [5–7].