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Line laser lock-in thermography for instantaneous imaging of cracks in semiconductor chips

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ABSTRACT

This study proposes a new line laser lock-in thermography (LLT) technique for instantaneous inspection of surface cracks in semiconductor chips. First, a new line LLT system is developed by integrating a line scanning laser source, a high-speed infrared (IR) camera with a close-up lens, and a control computer. The proposed line LLT system scans a line laser beam onto a target semiconductor chip surface and measures the corresponding thermal wave propagation using an IR camera. A novel baseline-free crack visualization algorithm is then proposed so that heat blocking phenomena caused by crack formation can be automatically visualized and diagnosed without relying on the baseline data obtained from the pristine condition of a target semiconductor chip. The proposed inspection technique offers the following advantages over the existing semiconductor chip inspection techniques: (1) inspection is performed in a noncontact, nondestructive and nonintrusive manner; (2) the crack diagnosis can be accomplished using only current-state thermal images and thus past thermal images are unnecessary; and (3) crack detectability is significantly enhanced by achieving high spatial resolution for thermal images and removing undesired noise components from the measured thermal images. Validation tests are performed on two different types of semiconductor die chips with real micro-cracks produced during actual fabrication processes. The experiments demonstrate that the proposed line LLT technique can successfully visualize and detect semiconductor chip cracks with width of 28–54 μm.

1. Introduction

Advances in semiconductor technologies have dramatically changed our lives since the 1960s and have allowed the development of high performance electronic devices such as personal computers and mobile phones. For example, smart phones would have not been possible without the development of subminiature and high performance semiconductors. The demand for lighter and more compact smart phones has necessitated the fabrication of smaller, thinner, and higher performance semiconductor chips. However, as the wafers used for semiconductor chips become thinner, a number of problems arise. One of the major issues is surface cracks on the chips. Because the surface cracks can compromise the performance and reliability of the final electronic devices, there is increasing demand to inspect semiconductor chips for surface cracks during the fabrication process [1–3].

A number of semiconductor chip inspection techniques have been proposed. Hilmersson et al. proposed an impact testing technique for detecting cracks in single-crystalline silicon wafers [4]. Although this technique requires only a simple test set-up and a short inspection time, the contact nature of this inspection can potentially cause damage to the target semiconductors. Sandler et al. applied noncontact eddy current sensors to identify micro-cracks [5], but strong current flows through chips can adversely affect the chip performance. Moreover, the application of the eddy current technique is limited only to conductive materials.

Other noncontact inspection techniques such as terahertz imaging [6,7], scanning acoustic microscopy [8], and light scattering techniques [9,10] have also been developed. The terahertz imaging technique has relatively high temporal and spatial resolution, making it sensitive to small damage. However, terahertz waves inherently have a short penetration depth, and more importantly they cannot penetrate metallic layers. Scanning acoustic microscopy has a much deeper penetration depth than terahertz waves, but it is not suitable for online inspection due to its long inspection time. For instance, scanning acoustic microscopy takes more than 10 min to scan a $100 \times 100\ mm^2$ semiconductor wafer [11]. In addition, the target semiconductor chip must be submerged into a water bath or at least covered with a water droplet for scanning acoustic microscopy. This may cause additional damage to the chip. More recently, a vision system was proposed as a promising alternative due to its noncontact nature,

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simple operation, and short inspection time. However, surface contamination and variation of lighting conditions often lead to positive false alarms. Although a number of inspection techniques have been proposed for chip crack monitoring, as listed above, a technique that addresses all of the aforementioned issues has yet to be developed and adopted in real fabrication processes.

In this study, a new line laser lock-in thermography (LLT) technique is proposed to overcome some of the aforementioned technical hurdles. The line LLT technique offers the following advantages for semiconductor chip inspection: (1) complete non-contact, nondestructive, and nonintrusive inspection; (2) baseline-free crack diagnosis using thermal images measured only from the current state without any prior thermal images; and (3) enhanced crack detectability by achieving high spatial resolution for thermal images and removing unwanted surrounding noise from the measured thermal images. To realize the line LLT technique, a new line LLT hardware system is assembled by integrating a line scanning laser source, an infrared (IR) camera with a close-up lens, and a control computer. A novel baseline-free crack visualization algorithm is then developed so that surface cracks can be automatically visualized without the baseline data obtained from the pristine conditions of the target semiconductor chip. Finally, its performance is experimentally verified using real semiconductor chips with micro-cracks.

This paper is organized as follows: Section 2 describes the hardware development of the proposed line LLT system and its working principle. In Section 3, the baseline-free crack visualization algorithm is developed. In Section 4, the experimental setup and results obtained from two different types of semiconductor chips are presented. Finally, this paper concludes with executive summary and discussion in Section 5.

2. Development of a line laser lock-in thermography (LLT) system

Fig. 1 shows an overall schematic of the proposed line LLT system composed of excitation, sensing, and control units. The excitation unit includes an arbitrary waveform generator (AWG), a continuous wave (CW) laser, and a line beam generator made of a plano-concave type cylindrical lens, a galvanometer scanner, and an F-theta lens. The CW laser used in this system has a wavelength of 532 nm and a maximum peak power of 15 W. Note that the laser peak power used in the experiment is only 120 mW (laser power intensity of 3.183 mW/mm^2), and this laser power intensity increases the surface temperature of a semiconductor chip up to 6 °C from the room temperature. It is known that this temperature increment level does not harm the semiconductor chip because the surface temperature of the semiconductor chip can rise up to 175 °C during manufacturing processes such as die attaching, wire bonding, and molding. The galvanometer scanner has a typical positioning speed of 40 rad/sec and an allowable scanning angle of $\pm$0.38 rad. The F-theta lens has a focal length of 1 m, and the beam width and length at the focal length are 1.3 mm and 100 mm, respectively. The sensing and control units are composed of an IR camera with a close-up lens and a control computer, respectively. The IR camera used in this study employs an uncooled microbolometer as an IR detector. The IR camera has an integration time of 13 ms, a temperature resolution of 0.03 K, 640 $\times$ 480 pixels, a sampling rate of 50 Hz, and a spectral range of 7.5–14 μm. The close-up lens has a focal length of 30 mm and a stand-off distance of 50 mm. The data acquisition and processing are respectively controlled by LABVIEW® and MATLAB® programs installed in the control unit.

The working principle of the line LLT system is as follows: first, the CW laser beam is modulated to a pulsed laser beam using AWG in the excitation unit, and the cylindrical lens transforms the shape of the pulsed laser beam from a point shape to a line shape. The control unit then sends out control signals to the galvanometer scanner, and the line laser beam is fired to a target surface through the galvanometer scanner and the F-theta lens. Subsequently, the line laser beam generates thermal waves at the desired excitation line and scans the target surface both horizontally and vertically so that randomly oriented cracks can be effectively inspected. Here, the crack direction can be randomly oriented, and the crack detectability can be affected by the direction of the line scanning. Multi-scans with varying line scan directions can address the crack direction issue. The corresponding thermal responses are captured by the IR camera in the sensing unit. Note that the excitation and sensing units are synchronized to each other so that the lock-in amplitude thermal responses can be precisely computed in the subsequent crack visualization algorithm. Next, the measured thermal responses are transmitted to and stored in the control unit. Finally, the measured data are processed using the crack visualization algorithm described below.

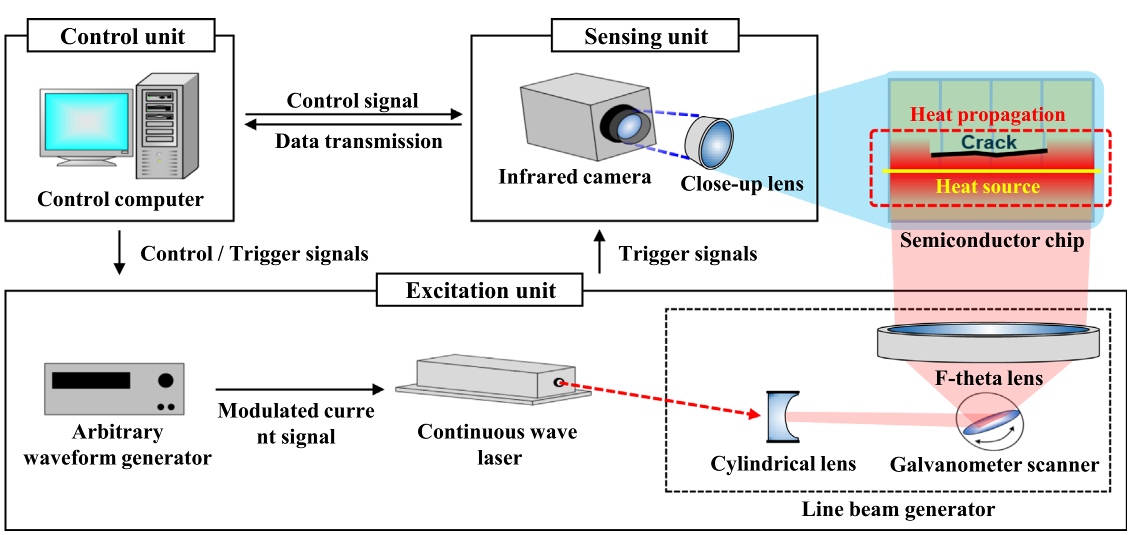

Fig. 1. Schematic of a line laser lock-in thermography system composed of excitation, sensing, and control units for semiconductor chip inspection: the control unit sends out control and trigger signals to the excitation unit to fire a line laser beam onto the target surface of a semiconductor chip for thermal wave generation. Simultaneously, the corresponding thermal responses are measured by the sensing unit. The measured thermal responses are then transmitted to, stored, and processed in the control unit.