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Wire sawing technology: A state-of-the-art review

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ABSTRACT

Wire sawing technology has been widely adopted for slicing of brittle-and-hard materials including crystalline silicon, SiC and sapphire. This paper presents a literature review on the research efforts on wire sawing related topics. First, the system and process level investigations of wire sawing technology, including both multi-wire slurry sawing and diamond wire sawing, are summarized. Ingot materials used in wire sawing technology, as well as their properties and behavior during sawing operation are discussed. As modeling and analysis of single grit indentation and scribing of brittle materials provide fundamental insight on material removal and these can be leveraged for wire sawing analysis at system level, a review of those models and modified models proposed particularly for wire sawing process are also presented. After the survey of current state-of-the-art, this contribution proposes important research aspects to be further worked on to gain more complete scientific understanding of wire sawing technology.

Contents

1. Introduction

Wire sawing technology has been widely used in manufacturing of brittle-and-hard materials such as silicon, SiC and sapphire. The boost of semiconductor and photovoltaic industry has been the primary drive of the development of wire sawing technology as crystalline silicon materials are used as the substrate in those industrial sectors and wire sawing technology provides an effective and efficient approach for wafering. Multi-wire slurry sawing (MWSS) was adopted as the process for semiconductor silicon wafer production as wafer size increased in the 1990s. Compared with other methods (such as Inside Diameter (ID) sawing and Outside Diameter (OD) sawing), the MWSS technique has the advantages of high throughput, smaller kerf loss and the ability to cut ingots of large size.

A schematic of the MWSS system for silicon wafering is shown in Fig. 1. A single stainless steel wire is fed from a supply spool through a pulley and tension control unit to the wire guides. Multiple strands of a wire web are formed by winding the wire through parallel grooves on the wire guides. The wire web is pulled by the torque applied by the main drive and slave rolls. In the meantime, the silicon ingot is fed against the moving wire web and sliced

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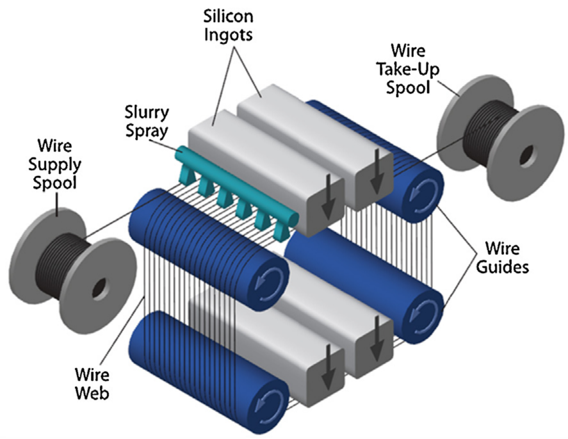

Fig. 1. Schematic of multi-wire slurry sawing of silicon wafers [1].

into hundreds or even more than one thousand wafers. Cutting is achieved by slurry SiC abrasives, which are supplied through nozzles over the wire web and carried into the sawing channel by the wire. The slurry carrier is typically oil or polyethylene glycol (PEG) based [2].

Recently, the multi-wire fixed abrasive diamond wire sawing (DWS) technology has rapidly gained industrial attention due to its potential for two to three times higher productivity and the potential for kerf recycling. Instead of using SiC grits in slurry as cutting agents, the stainless steel wire used in DWS is impregnated or electroplated with diamond grits serving as fixed cutting points. Water based coolant is typically used. An example of the commercially available diamond wire is shown in Fig. 2.

Although the operation systems share similar features, the MWSS is fundamentally different from the DWS process from the standpoint of material removal mechanism. As shown in Fig. 3(a), the schematics of the sawing channel, material removal in slurry sawing is achieved by the interactions between the SiC particles, the wire and the Si substrate. This process is referred to as three-body-wear in tribology. In DWS, however, the Si substrate is removed through two-body-wear, which involves the direct interaction of the diamond grits with the silicon ingot materials, as shown schematically in Fig. 3(b).

Although wire sawing technology has been used in industry for decades, research efforts on this complicated manufacturing process have been very limited until recent years. The recent boom of crystalline silicon photovoltaic industry significantly promoted research interest in this abrasive manufacturing technology. Various aspects of wire sawing technology have been investigated. This

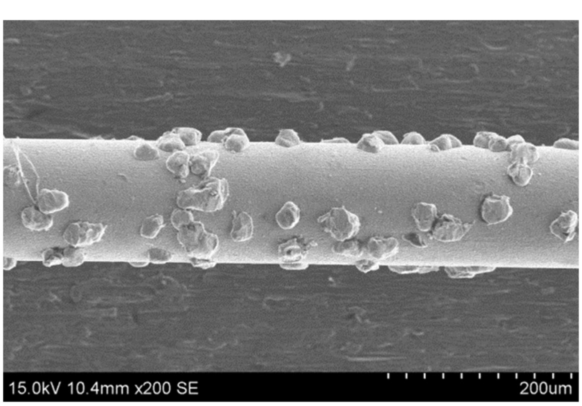

Fig. 2. Scanning electron microscope (SEM) image of diamond wire. Diamond grits are covered by Ni-based coating alloy.

contribution aims to summarize relevant research work in a systematic manner. Section 2 provides a summary of the system and process level investigations of wire sawing technology, including both MWSS and DWS. Section 3 discusses the materials used in wire sawing technology, as well as their properties and behavior during sawing process. As modeling and analysis of single grit indentation and scribing of brittle materials provide fundamental insight on material removal in sawing process and those models have been leveraged in system level analysis, a review of those research efforts are presented in Section 4. After the survey of current state-of-the-art, Section 5 proposes important research aspects to be further worked on to gain thorough understanding of wire sawing technology.

2. Modeling and experimental studies at system and process level

Wire sawing is a very complicated manufacturing process involving various factors and their interactions. Process parameters include wire tension, wire travel speed, feed speed, SiC (or diamond) grit size, distribution and density in slurry (or on diamond wire), etc. The material removal happening in the sawing channel is determined by wire, cutting grit (SiC or diamond) and hydrodynamic fluid environment. Temperature can affect the friction and lubrication conditions of the sawing channel, thus the overall sawing performance. Vibration may lead to severe wear or even breakage of wire and generation of saw marks. A number of research groups have looked at different aspects of wire sawing at system and process level. The majority of the research attention has been focused on MWSS system, while the studies of DWS have been focused on design and analysis of diamond wires since other factors in the process are similar to those in the MWSS system.

2.1. Multi-wire slurry sawing

Kao et al. [4–9] were one of the first research groups to study the MWSS system for manufacturing of semiconductor grade silicon wafers. Their effort lasted about a decade and their activities are summarized as shown in Fig. 4 Their work can be classified into three major aspects: cutting mechanism, material removal rate and saw damage. The yellow blocks on the right side of Fig. 4 present their pertinent work on each aspect.

Li et al. [4] developed a contact stress model of the interactions between the wire, ingot, and abrasives in the MWSS process. Abrasives in the slurry are treated as loose third-body particles caught between the wire and the ingot surface. Material removal is attributed to the simultaneous rolling and indenting action of the abrasives on silicon. This is referred to as the rolling–indenting model of material removal. The contact stress induced by a cone-shaped cutting grit was calculated based on superposition of stress fields resulting from the normal and tangential loads. It should be noted that their results are only valid for elastic deformation due to the application of linear superposition principle.

Following the rolling–indentation modeling work, the indentation elastic stress fields created in silicon by an axisymmetric indenter was solved by Yang and Kao [5]. The elasto-hydrodynamic interactions between the slurry and wire in MWSS were analyzed using the finite element method [6]. The resulting analysis yielded a film thickness profile and pressure distribution as a function of wire speed, slurry viscosity, and slicing conditions. It was shown that slurry-based wire sawing is characterized by “floating” machining conditions where the minimum film thickness is greater than the average abrasive size. In addition to the “rolling–indenting” model, a “scratching–indenting” model was proposed as the cutting mechanism by Yang and Kao [7].