International Journal of Machine Tools & Manufacture 66 (2013) 54–65

Contents lists available at SciVerse ScienceDirect

International Journal of Machine Tools & Manufacture

journal homepage: www.elsevier.com/locate/ijmactool

Origin, modeling and suppression of grinding marks in ultra precision grinding of silicon wafers

F.W. Huo*, R.K. Kang, Z. Li, D.M. Guo

Key Laboratory for Precision and Non-Traditional Machining Technology of Ministry of Education, Dalian University of Technology, Dalian 116024, China

ARTICLE INFO

Article history:
Received 17 September 2012
Received in revised form
22 November 2012
Accepted 29 November 2012
Available online 10 December 2012

Keywords:
Silicon wafer
Grinding marks
Cup wheel
Axial run out
Flatness
Waviness

ABSTRACT

A phenomenon commonly encountered in grinding of silicon wafers is the grinding marks, which are difficult to remove by subsequent polishing process, and have been a great obstacle to the manufacture of silicon wafers with higher flatness. In this paper, the grinding marks formation mechanism was clarified, a grinding marks formation model and an angular wavelength model were developed, and a grinding marks suppression method was proposed. A series of grinding experiments were carried out to verify the developed models and investigate the effect of the wafer rotational speed, the wheel rotational speed, the infeed rate, the axial run out of the cup wheel and the spark out time. The results show that: (1) grinding marks are waviness generated on silicon wafers caused by non-uniform material removal circumferentially due to the axial run out of the cup wheel; (2) grinding marks present multiple angular wavelengths characteristics; (3) the angular wavelength of grinding marks is a one-variable function of the rotational speed ratio of the wheel to the wafer; and (4) grinding marks could be suppressed significantly by properly selecting the rotational speed ratio.

1. Introduction

Silicon wafers used as substrates for the production of semiconductor devices have to be extremely flat and smooth to meet the flatness and nanotopography requirements [1,2]. As the device feature size reduces continuously, the requirements associated with these parameters become increasingly stringent [3]. In past ten years, a trend using the rotational grinding method to produce silicon wafers with high flatness and minimal damage cost effectively has been highlighted [4,5]. However, grinding marks are induced in both single side rotational grinding and double side rotational grinding [6–8]. The flexible polishing pad is prone to deform according to the shape of the waviness when the silicon wafer with grinding marks is subjected to subsequent chemical mechanical polishing process, and they may remain even after a considerable amount of material removal. Therefore, grinding marks have significant impact on site flatness and nanotopography of the final polished silicon wafers, and have been a great obstacle to the production of ultra flat wafers [6,7]. Additional processes such as slight wet etching, low damage lapping and plasma etching have been tried to remove them and improve wafer flatness [9–11]. In order to reduce grinding marks, Kato et al. proposed to control the wafer rotation speed to be low enough in the spark out grinding stage; whereas Vepa et al. suggested varying the wafer rotational speed relative to the cup wheel rotational speed during grinding [12,13]. Research related to wafer grinding marks could be retrieved to the 1990s, when Tonshoff et al. [14] firstly reported the grinding marks in grinding of silicon wafers, and argued that they are the characteristics for the wafer rotational grinding. Pei et al. [15] studied in 2002 the effects of grinding process parameters on grinding marks through a series of grinding experiments. Chidambaram et al. then developed a mathematical model to predict the locus of the grinding lines and the distance between two adjacent grinding lines. The relationships between grinding marks and various process parameters were then discussed according to the developed model [6,7]. This model can predict grinding line locus well, but its prediction of line distance is correct only when the rotational speed ratio of wheel to the wafer is very low. Sun et al. [16] studied further the effect of the shape of the wafer chuck on grinding marks in grinding of silicon wafers, and developed a mathematical model to predict the depth of grinding marks for different chuck shapes. Recently Li et al. [8,17] investigated systematically the grinding marks in simultaneous double side grinding when the rotational speed ratio of the wheel to the wafer is an integer and developed a mathematical model for the distance between adjacent grinding marks. They found that the distance between the adjacent grinding lines increases and the grinding lines tend to become less curved with the increase in the ratio. However, this model was not capable of

* Corresponding author. Tel./fax: +86 411 84707430.
E-mail address: huofw@dlut.edu.cn (F.W. Huo).

0890-6955/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijmachtools.2012.11.006

predicting the grinding marks pattern when the ratio is a non integer. Li et al. [18] further proposed an extended model for the grinding marks pattern suitable for both integer and non-integer ratios. Despite this, the generation mechanism of grinding marks has not yet been fully clarified, the models developed so far are not capable of characterizing satisfactorily the angular wavelengths of grinding marks and predicting the grinding marks pattern, little has been written on how grinding parameters affect grinding marks, and practical measures for suppressing grinding marks are less than satisfactory. The aim of the present paper is to rectify these situations. It is divided into seven sections. Section 1 is introduction. The generation mechanism of grinding marks is clarified in Section 2. A grinding marks formation model and an angular wavelength model of the grinding marks are developed in Sections 3 and 4, respectively. Section 5 is the experiments. A method for suppressing grinding marks is proposed in Section 6. Finally, conclusions are drawn in Section 7.

2. Formation mechanism of grinding marks

Grinding induced waviness is generally considered to be caused by grinding vibrations such as forced vibration and self-excited vibration [19–24]. However, we found that it is the axial run out of the cup wheel rather than grinding vibrations that causes non-uniform material removal circumferentially and results in grinding marks on silicon wafers. In wafer rotational grinding, a segmented diamond cup wheel with a grinding layer that is only a few millimeters wide is used to perform an infeed grinding [14,25]. To produce extremely flat surface, it is absolutely necessary that all the individual segments held on the wheel flange are uniform in height. However, more or less run out on the end face of the cup wheel practically always arises. It may arise from a number of sources such as cup wheel axis offset and tilt, errors in truing and dressing of the cup wheel, and non-uniform wear of individual wheel segments.

The axial run out of the grinding wheel may not be problematic for traditional grinding operations, where, the wheel depth of cut usually is much larger than the run out. However, since the wafer usually rotates in the range from several tens to several hundreds of revolutions per minute and the infeed rate is usually in the range from several to several tens of micrometers, the wheel depth of cut falls into a range from several tens of nanometers to several micrometers. Therefore the run out of the cup wheel and wheel depth of cut have almost the same order of magnitude and the effect of wheel run out cannot be neglectable [26]. When there exists axial run out, each of the protruding segments above the average working surface of the cup wheel will perform an additional cutting action and generate an extra groove on the wafer per revolution of the cup wheel, as illustrated in Fig. 1.

A remarkable characteristics of the wafer rotational grinding is that the kinematics of the cup wheel relative to the wafer is periodical. This means that any cutting point on the cup wheel, if neglecting the infeed motion of the cup wheel, will repass the same cutting path generated just a period before. However, the previous grooves generated early enough during the infeed grinding will be completely removed or partially removed and only a limited number of grooves can survive when the grinding operation is over. Moreover, these survived grooves are not evenly distributed circumferentially but aggregate within some particular regions and result in grooves much wider in most situations. These large and small grooves form the grinding marks eventually. For ease of reference, the individual grooves generated by the most protruding segment are referred to as the elementary grooves and the wider are referred to as the resultant grooves.

The non-uniformity distribution of the grooves in wafer grinding is easy to understand by drawing the cutting path of an individual

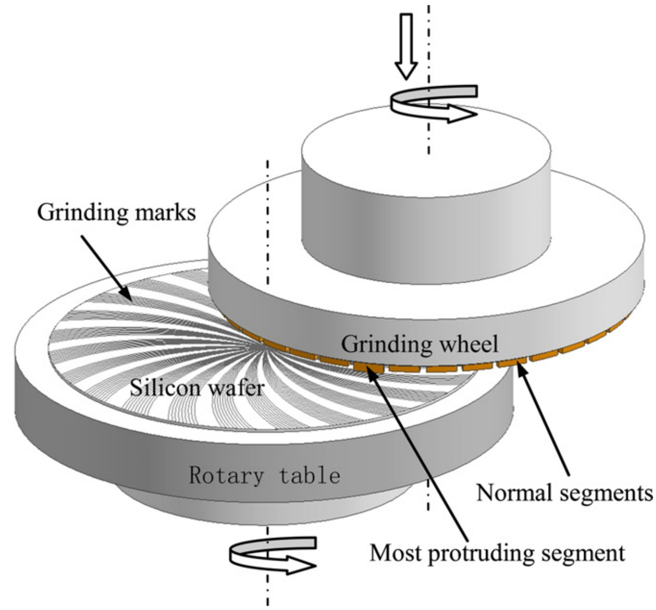

Fig. 1. Illustration of the grinding marks formation in wafer rotational grinding.

cutting point, as shown in Fig. 2, where the curves drawn by black solid line represent the survived grooves and the dash line curves represent the motion trajectory of the cutting point. The periodic motion of the cutting point relative to the wafer and the concentration of the cutting paths are self-evident. When the wheel depth of cut is larger than the height of the protruding segment only 15 grooves could survive; whereas 90 grooves could survive if the wheel depth of cut is six times the height of the protruding segment though other parameters are identical. In wafer rotational grinding, since only the wafer rotation motion is required for the purpose of wafer surface generation, all the cutting points of the cup wheel begin their contact with the wafer at the center region and follow the same identical forward-curved paths extending radially outward from the center and they do not cross each other except at the center region. This non-crossing property enables the shapes of the grooves to be intact and enables them to overlap each other to the most.

3. Grinding marks formation model

The practical generated wafer surface is the superposition of the ideal generated wafer surface without taking grinding marks into consideration and the survived grooves. Since every rotation of the cup wheel leaves a groove of some width and depth on the wafer surface. The geometry of a groove can be represented by means of a cross-section and a path over the wafer surface. Thus the grinding marks formation model could be derived by calculating the Boolean difference of the ideal generated wafer and the geometry solids representing the grooves generated by the protruding segment of the cup wheel. Three coordinate systems are used for the model development, as shown in Fig. 3. Point O and Point O_1 are designated as the wafer and the wheel centers, respectively. The coordinate system $O(X, Y, Z)$ is fixed on the wafer center. The coordinate system $O_1(X_2, Y_2, Z_2)$ is fixed on the cup wheel center. We only consider the most protruding segment, since it produces the deepest grooves and these grooves are the main composition of the grinding marks. For simplicity, the most protruding segment was assumed to be a cutting point. Suppose that the wafer is stationary and the cup wheel rotates about its own center at a speed of n_2 and orbits simultaneously around the