行政院國家科學委員會專題研究計畫成果報告

精密電解削銳輪磨加工硬脆材料之研究

A Study of Precision ELID Grinding of Brittle Materials and the Integrity of the Obtained Surfaces

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1.中文摘要

矽單晶等材料一般被歸類為"脆性材料"。因為當這些材料承受應力時, 在還沒有產生明顯之塑性變形前脆裂破壞便已發生。 雖然這種高脆度(Brittleness)**使得加工這些材料變得極為困難, 但對由這些脆性材料製成之高精度零件如晶圓**(Wafers) **等的需求卻與日俱增；只因為他們擁有許多現代及未來科技運用所需之優良的物理、機械、光或電子特性。也因此改進對這些脆性材料之加工技術變得極為重要亦極具開發潛力。近幾年來英、美、日、德等國投入了大量的人力物力從事這方面之研究, 企圖開發出一種可行之加工脆性材料的方法, 也就是基於這種方法之開發成功可獲致的經濟效益。**

ELID**線上削銳之精密輪磨雖使超微粒磨料磨輪之輪磨加工成為可行，如果“**ELID**削銳之各項參數選取控制得當”則其加工所得之結果可與研磨與拋光過程產生之奈米級表面粗糙度之光學等級表面相比美(而如果**ELID**削銳之各項參數選取控制不當則其加工所得之結果常為表面粗糙度及形狀精度不盡理想且磨輪損耗過快)。但問題是甚麼是“得當之**ELID**削銳參數”？ 這些參數如何取得？且其與所用之磨輪及輪磨加工條件間又有何關係？這些問題皆因未能對**ELID**過程有足夠了解而難以取得較完整之答案。也因此**ELID**削銳參數之選取目前仍多以嘗試錯誤及累積經驗的方式進行;不但耗時費力且一但所用之磨輪或切削液等有所更改則又必須經歷另一次嘗試錯誤及累積經驗的過程. 是故欲使**ELID**削銳參數之選取步上較有系統而合理快速之方向，必須對**ELID**削銳之各項參數及磨輪特性對加工表面造成之影響有進一步之認識與瞭解。**

本研究計畫之目的既為應用 ELID **削銳之精密輪磨加工技術對矽單晶進行加工並針對** ELID **削銳之各項參數對加工表面造成之影響及磨輪特性對加工表面造成之影響進行分析.**

關鍵詞：超精密加工，鑽石輪磨，ELID **線上削銳**

Abstract

In order to machine the 300mm~400mm silicon wafer to the specified surface roughness and flatness, ELID diamond grinding were employed in this study to investigate its feasibility. Cast iron fiber reinforced diamond wheels were used to grind silicon wafers and various ELID parameters were systematically tested to examine their influences on the grinding process. The results showed that, under the same grinding conditions, the obtained surfaces were characterized by (1) thick poly/amorphous layer with occasionally deep-penetrated cracks, (2)thick amorphous layer(up to 250nm) with distributed dislocation loops(~300nm into the substrate), and (3)thin amorphous layer (up to 30nm) when (1) no ELID, (2) ELID with rather low peak voltage and current and (3) ELID with high peak voltage and current were applied in the grinding processes.

Keywords: precision machining, diamond grinding, ELID grinding

2. Introduction(緣由與目的)

Single crystal silicon, having many advanced physical and mechanical properties, is now widely used in the semiconductor industry (account for more than 90% of the semiconductor devices). Owing to the increasing demands on brittle materials such as advanced ceramics, glasses and single crystal silicon, researches on ductile-mode grinding and related cutting theories, material removal mechanism have attracted many researchers' attention[1~8]. As a results, the traditional lapping, etching, polishing routine of making wafers is suggested by many researchers to be replaced by precision grinding and polishing if the requirements of flatness, TTV and roughness are to be fulfilled when producing 12"~16" wafers. In order to minimize the polishing works and the resulted deterioration of form accuracy, it is important to reduce the grinding induced surface/subsurface damage. It is well-known that the grit size of abrasive on the grinding wheel has profound effect on the obtained surface roughness. Generally speaking, the smaller the grit size, the better surface finish and the less damaged layer could be achieved. However, when abrasive gets smaller the wheel has bigger chance to be loaded by swarf (chips). As a result, the wheel constantly needs to be redressed and the the process becomes impractical to be employed in the real production. The ELID (electrolytic in-process dressing) technique(Figure 1), developed by Ohmori[9], offers a way of in-process monitoring/dressing the grinding wheel which enables the wheel of ultra-fine abrasives to be used. Although many good results have been reported in various application fields over the years[10~13], problems like "what are the effects of ELID conditions on the obtained surface/subsurface", "what are the optimized ELID conditions for a specified grinding set-up and how to get it"… are still quite some distance from fully understood and need further investigations.

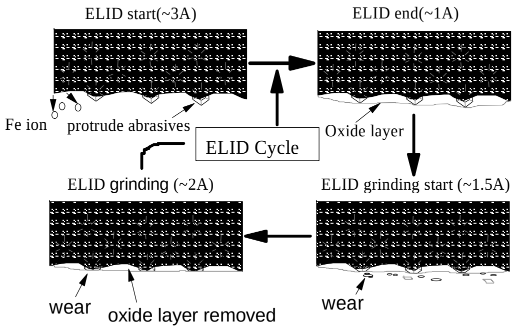

Figure 1 Schematic representation of ELID grinding process

3. Experimental Setup

A Nachi RGS20N ELID grinding machine was used in this study for carrying out grinding experiments. The power supply and metal bond diamond wheels were made by Fuji (ELIDer 630) and Noritake respectively. Shown schematically in Figure 2 is the lay-out of the grinding experiments. The (100) silicon wafer was placed on the work spindle which was set to rotate at a relatively low speed (100~400rpm). The grinding head was set to operate at the speed of 1000 to 3000rpm. The feed rates, peak voltages and peak currents ranged respectively from 2μm/min to 8μm/min, from 30V to 60V and from 2A to 10A. A pulse duration (Ton/off) of 2μSec and gap of 0.4mm were used in the study. Specimens ground under various ELID conditions and grinding parameters were subsequently observed using SEM(scanning electron microscope), AFM(atomic force microscope) and HRTEM(high resolution transmission electron microscope) to analyze its surface and subsurface.

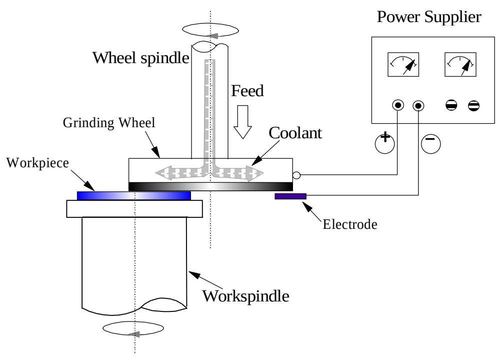

Figure 2 Schematic representation of the setup of grinding experiments

4. Results and Discussions

Based on the results of previous researches[11], the grow-rate of the oxide layer increased with increasing peak voltage(Vp), peak current(Ip) and pulse duration (Ton/off). Since the loosen structure of the oxide layer can prevent wheel from clogging with chips, thicker layer normally means wheel is better protected from loading. However, the oxide layer is the product of oxidation process of metal bond and wheel is protected from loading in the expense of sacrificing(consuming) the bonding material of abrasives. In the case of having a thin oxide layer (low Vp, low Ip and/or shorter dressing time) or not using ELID at all, the wheel subjects to a bigger chance to be loaded. The occurrence of loading will inevitably result in inefficient cutting, large amount of friction heat, surface/subsurface damages and loss of dimension accuracy. How are the oxide layer and grinding parameters work together to generate the surface? What are their effects on subsurface damage layer? In order to probe into these questions, a series of grinding experiments were conducted in this study. Based on its ELID conditions, these experiments could roughly classified into categories: (1) thick oxide layer (2) thin oxide layer and (3) no ELID.

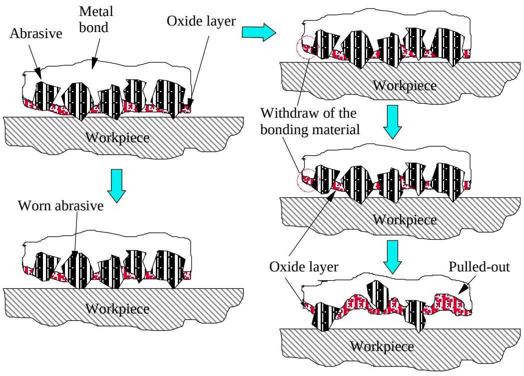

Figure 3 Schematic illustration of the progressive changes of the surface of a thick oxide layer covered grinding wheel during ELID grinding silicon with small feedrate (left) and large feedrate conditions.

Shown in Figure 3 is the schematic illustration of the progressive changes of the surface of a thick oxide layer covered grinding wheel during ELID grinding silicon. Owing to the thick oxide layer, no loading occurs in both cases (small/large feedrate). However, in comparison to the case of low feedrate, the cutting force is relatively higher when the feedrate is high. The higher cutting force and the fast withdrawing bonding substrate due to the oxidation process have made the protruding grains to be pulled out before it gets significant attritious wear. This will produce sharp new protruding grains so that a stable cutting condition can be reached. In the case of thick oxide layer and low feedrate, there is still chances for some protruding grains getting excess attritious wear before it is pulled out because of the low cutting force. The worn grains will dull the wheel and generate much friction heat and subsurface damage.

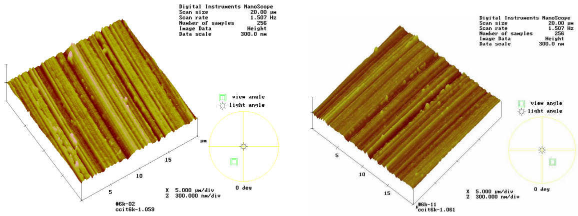

Figure 4 AFM micrographs of the ELID ground silicon surfaces using #6000 diamond wheel and 60V, 10A, 3000/100rpm, 8μm/min(left); 60V,10A, 3000/100rpm, 2μm/min(right)

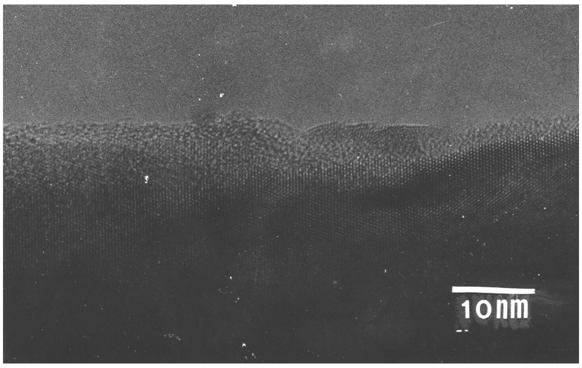

Figure 5 HRTEM micrographs of the ELID ground silicon surfaces using #6000 diamond wheel and (60V, 10A, 3000/100rpm, 8μm/min), zone axis : [110]

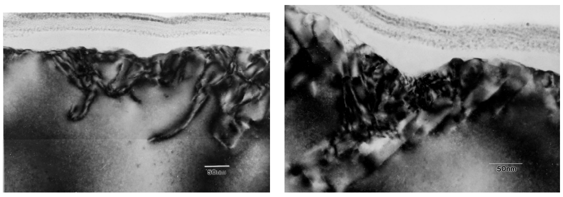

Figure 6 HRTEM micrographs of the ELID ground silicon surfaces using #6000 diamond wheel and (60V, 10A, 3000/100rpm, 2μm/min), zone axis : [110]

Shown in Figure 4 are the AFM micrographs of the ELID ground silicon surfaces using #6000 diamond wheel 60V, 10A, 3000/100rpm and feedrates of a)8μm/min (b) 2μm/min. Little differences can be observed from these micrographs. The differences between these two conditions can be clearly seen in Figure 5 and Figure 6 where subsurfaces of the ELID ground silicon were examined under HRTEM. Single crystal substrate covered by an amorphous layer of 10~30nm in thickness when thick oxide layer and high feedrate was used. While grinding with thick oxide layer and low feedrate, as illustrated earlier, excess attritious wear might occurs and the generated friction heat/force introduced a thicker amorphous layer(up to 80nm) and the dislocation distributed layer (up to 200nm) underneath it (shown in Figure 6).

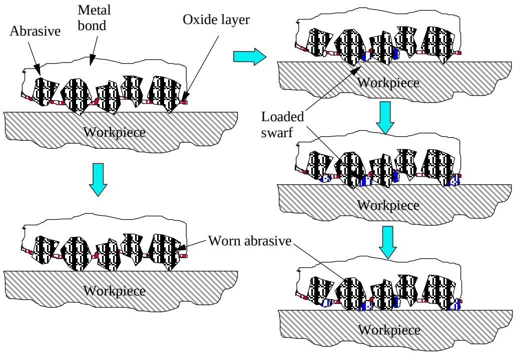

Figure 7 Schematic illustration of the progressive changes of the surface of a thin oxide layer covered grinding wheel during ELID grinding silicon with small feedrate (left) and large feedrate conditions.

Shown in Figure 7 is the schematic illustration of the progressive changes of the surface of a thin oxide layer covered grinding wheel during ELID grinding silicon. The low cutting force and slowly reducing bonding force make the replacement of the worn grain too slow to prevent wheel from getting dull and friction heat from increasing. In the case of low feedrate, the oxide layer generated by electrolytic process can still keep pace with the loss caused by the cutting process. Increasing the feedrate will fasten the loss rate and break the balance which means that the wheel will be clogged with chips in time. In both cases, the bonding materials are etched away rather slowly so that the grains cannot be dislodged so easily. As a result, some protruding grains may get excess attritious wear before they are pulled out and this will dull the wheel and generate much friction heat and subsurface damage.

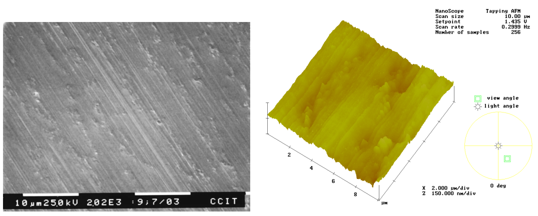

Figure 8 SEM and AFM micrographs of the ELID ground silicon surfaces (#6000, 30V, 2A, 2000/400rpm, 2μm/min)

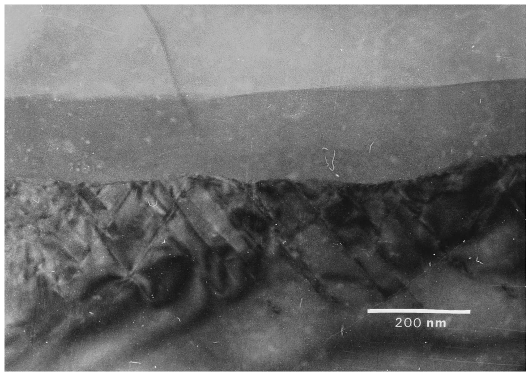

Figure 9 HRTEM micrographs of the ELID ground silicon surfaces (#6000, 30V, 2A, 2000rpm, 400rpm, 2μm/min) zone axis：[110]

Shown in Figure 8 was the SEM and AFM micrographs of the ELID ground silicon surfaces (#6000, 30V, 2A, 2000/400rpm, 2μm/min). Discontinuous machining marks left by the loaded wheel were clearly seen. Thick amorphous layer(up to 250nm) with distributed dislocation loops(~300nm into the substrate) were the typical subsurface pattern of this type of ELID and grinding conditions(Figure 9). Amongst the thick amorphous layer, some scattered nano-crystals could be observed in the HRTEM micrographs (lattice images). This means that the surface has experienced rather high temperature and stayed in high temperature for a duration enough for nanocrystals to form in the amorphous layer.

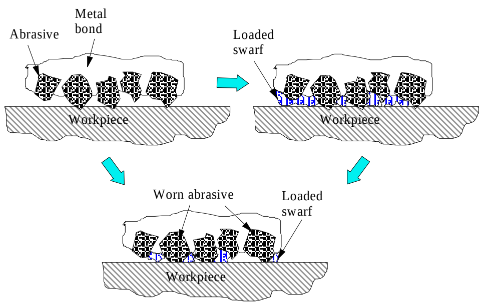

Figure 10 Schematic illustration of the progressive changes of the surface when grinding silicon (without ELID) with small feedrate (left) and large feedrate conditions.

When grinding with no oxide layer (without ELID), low feedrate or high feedrate, it is only a matter of time for the grinding surfaces of the wheel become clogged with swarf. Dull wheel caused by excessive attritious wear of the grains is another sure thing to happen.

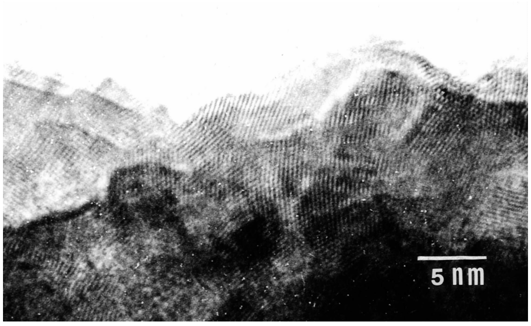

Figure 11 HRTEM micrographs of the ground silicon surfaces (2000rpm/400rpm, 2μm/min, without ELID） Zone axis：[110]

Thick poly/amorphous layer (up to 500nm) with distributed dislocation loops(~300nm into the substrate) and occasional deep-penetrated cracks observed on the HRTEM micrographs of the ground silicon surfaces (Figure 11) is an indicator showing the surface has experienced rather high temperature and stayed at high temperature for a duration enough for polycrystalline silicon to form.

5. Conclusions

1. The ELID generated oxide layer can prevent wheel from clogging with chips, thicker layer normally means wheel is better protected from loading. However, the oxide layer is the product of oxidation process of metal bond and wheel is protected from loading in the expense of sacrificing(consuming) the bonding material of abrasives.
2. Thick oxide layer and high feedrate favors wheel to produce sharp new protruding grains so that a stable cutting condition can be reached. In the case of thick oxide layer and low feedrate, there is still chances for some protruding grains getting excess attritious wear before it is pulled out. The worn grains will dull the wheel and generate much friction heat and subsurface damage.
3. In the case of thin oxide layer and low feedrate, the oxide layer generated by electrolytic process can still keep pace with the loss caused by the cutting process. Increasing the feedrate will fasten the loss rate and break the balance which means that the wheel will be clogged with chips in time. In both cases, the bonding materials are etched away rather slowly so that the grains cannot be dislodged so easily. As a result, some protruding grains may get excess attritious wear before they are pulled out and this will dull the wheel and generate much friction heat and subsurface damage.
4. When grinding with no oxide layer (without ELID), low feedrate or high feedrate, it is only a matter of time for the grinding surfaces of the wheel become clogged with swarf. Dull wheel caused by excessive attritious wear of the grains is another sure thing to happen.
5. Depending on the temperature history experienced during the grinding process amorphous, nano-crystals and poly-crystalline layers could be observed existing in the ground silicon specimens.

6. 計畫成果與自評

1. **瞭 解 電 解 削銳之精密輪磨加工技術對矽單晶等硬脆材料進行延性輪磨加工時砂輪之動態電解特性。**
2. **探 討 電 解 削銳之各項參數對加工表面造成之影響。**
3. **分 析 精密輪磨加工硬脆材料時其主要之材料去除機制。**
4. **瞭 解 加工表面與次表面之顯微組織變化及其與加工參數間之關係。**
5. **分 析 精密輪磨加工硬脆材料時加工表面特性與其次表面特性間可能存在之相關性。**
6. **參與本計畫之研究人員可獲得電 解 削銳精密輪磨加工技術對矽單晶等硬脆材料時之微變形機構、表面及次表面之顯微組織變化及電 解 削銳、精密輪磨各項參數對其之影響等相關技術之訓練與分析能力之建立。**

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